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Single-Mode Operation of a Tunable Visible Laser Diode

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Single-Mode Operation of a Tunable Visible Laser Diode

by

Matthew E. Davis

April 28, 2014

The report of the investigation undertaken as a Senior Thesis,
to carry two courses of credit in the Department of Physics

Michael T. Orr
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Elizabeth W. Fischer

ABSTRACT

The purpose of this thesis is to describe the construction and operation of a single mode, tunable, external cavity diode laser for use in the excitation of lithium atoms. I will report the relevant ideas required to understand laser diode operation as well as the various quantum states of lithium. The primary focus of this experiment is to construct a tunable external cavity diode laser at 670.8 nm to be used in future experiments on lithium.

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I. INTRODUCTION

The development of the LASER (Light Amplification by Stimulated Emission of Radiation) has provided the necessary tools needed to study the interaction between light and matter. The ultimate goal of the work that I have been doing over my senior year is to implement a diode laser into an external cavity system. The diode laser that has been chosen has a peak operating wavelength that coincides with the transitions needed to excite lithium atoms. Ultimately, lithium atoms in an atomic beam may be used to study the phenomenon of electromagnetically induced transparency without the usual complications of atomic collisions and the Doppler effect.

The first contribution that I made to this project was to collimate the emission from the diode laser. The next step was to implement a diffraction grating to provide feedback to the diode laser. After the grating had been properly, set the external cavity diode laser had to be adjusted so that it would operate at 670.8 nm. I then had to construct a circuit that would allow the ECDL to be scanned through a range of frequencies by applying a voltage ramp to a piezoelectric transducer as well as the current controller. The final step was to adjust the settings of the control box so that the laser would continuously scan through a frequency range to observe both transitions associated with lithium.

In this thesis I will briefly describe the hydrogen atom as well as the relevant theories of stimulated emission, absorption, and spontaneous emission. I will then describe how a diode laser works and the necessary conditions required for stimulated emission to occur. In the next section, the apparatus will be introduced. I will focus mainly on the important elements required for laser operation and tuning. I will begin by introducing the external cavity diode laser, followed by the collimation of the diode laser.

Next, I will discuss the importance of the diffraction grating and the control circuit that was constructed. Then I will discuss the wavemeter and the spectrum analyzer that are used to monitor the output of the ECDL. Afterwards, I will introduce the optical isolator and its importance to the apparatus. I will finish the thesis by presenting the data that was collected to help characterize the output of the ECDL.

II. THE HYDROGEN ATOM

The Rutherford model of the atom places a dense positive charge (nucleus) at the center of an orbiting electron. Rutherford's theory explained the results of his scattering experiment perfectly; however, his model had the major drawback of being inherently unstable. This instability arises from the fact that an accelerating point charge will release energy in the form of electromagnetic radiation causing an orbiting electron to fall towards the nucleus.[1] As the electron descends toward the nucleus it should emit a rainbow of colors. However, experimental observations revealed that this was not the case and a discrete spectrum of hydrogen was observed.

In 1913, Niels Bohr proposed a refinement to the Rutherford model by suggesting that the orbiting electrons are restricted to discrete energy levels within the atom[2]. Bohr derived possibly one of the most important fundamental results in quantum mechanics with the introduction of the Bohr formula

$$E_n = \frac{1}{n^2}\left[-\frac{m_e e^4}{2(4\pi\varepsilon_0)^2\hbar^2}\right], \tag{1}$$

or

$$E_n = \frac{E_1}{n^2}, \qquad (2)$$

where m_e is the mass of the electron, $\hbar$ is planks constant multiplied by 2π, e is the charge of the electron, ε_0 is the permittivity of free space. The term in the brackets can be simplified to the ground state energy of hydrogen, E_1. In this equation, n, is known as the principle quantum number and it describes an integer number of quantized energy levels of the atom. I will explain this quantum number in further detail in following sections. After inspecting the spectral lines of the hydrogen atom, Bohr realized that the frequencies of light in the spectrum corresponded to discrete energy levels. These energies can be directly related through Planck's constant

$$\Delta E = E_b - E_a = -E_1 \left[\frac{1}{n_a^2} - \frac{1}{n_b^2}\right] = h\nu. \qquad (3)$$

In this case, $E_1 = -13.6$ eV. This can be understood when electrons make transitions from one energy level to another, emitting a photon of energy equal to the change in energy levels (Fig. 1).

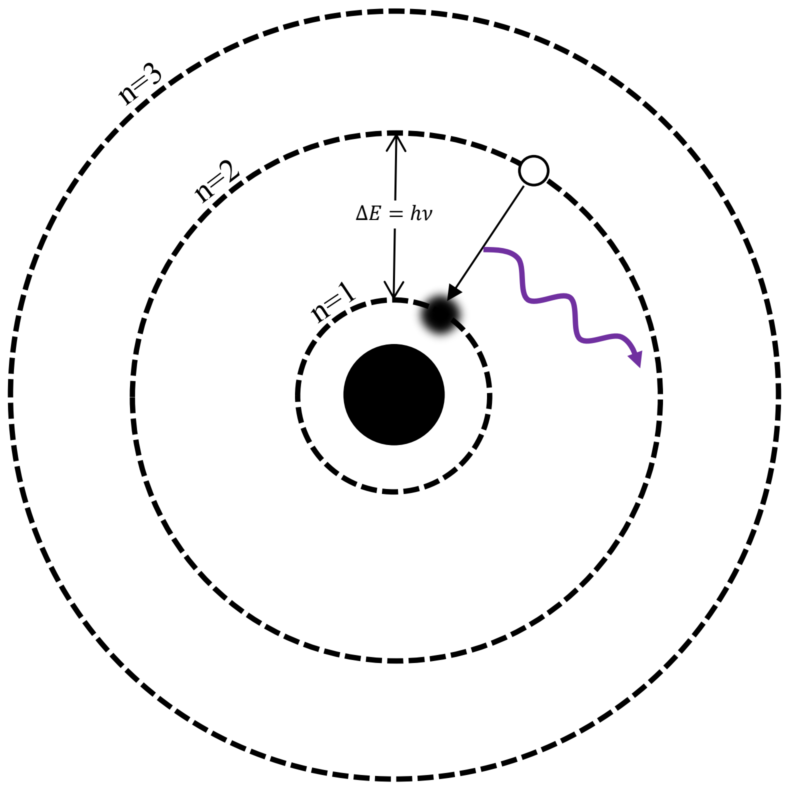

FIG. 1**.** Diagram showing a hydrogen atom making a transition from the $n = 2$ orbit to the $n = 1$ orbital emitting a photon with energy equal to the change in energy of the transition.

III. STIMULATED EMISSION, ABSORPTION, SPONTANEOUS EMISSION

A. Introduction

If the hydrogen atom is in a particular state, then in principle it should remain there forever. However, if the atom is *perturbed* by shining light (electromagnetic radiation) on it, there is a chance the atom will make the transition to an excited state by absorbing the energy of the photon in a phenomenon known as absorption. While in this excited state, there is a chance that the electron will make a transition down to another energy level, thus releasing a photon with energy equal to the differences in the energies of the states involved.

B. **Stimulated emission**

Stimulated emission is a process which states that if a particle is in an upper state, $|b\rangle$, and light is shined on it with the same energy as the transition, the atom can make a transition to the lower state, $|a\rangle$. The probability of this transition is the same as the transition to the upper state as seen by the symmetry of the following equations[3]

$$P_{a\to b}(t) = \left(\frac{|\wp|E_0}{\hbar}\right)^2 \frac{\sin^2\left[2\pi(\nu_0-\nu)\frac{t}{2}\right]}{\left(2\pi(\nu_0-\nu)\right)^2}, \tag{4}$$

and

$$P_{b\to a}(t) = \left(\frac{|\wp|E_0}{\hbar}\right)^2 \frac{\sin^2\left[2\pi(\nu_0-\nu)\frac{t}{2}\right]}{\left(2\pi(\nu_0-\nu)\right)^2}. \tag{5}$$

Here, $\hbar = \frac{h}{2\pi}$. This concept is crucial to the operation of lasers because the electromagnetic field gains energy $\hbar\omega_0$ from the atom. It can be said that one photon went in and two came out, the one that caused the transition down and another from the transition itself (Fig. 2). [4] The importance of stimulated emission will be elaborated upon in the laser section.

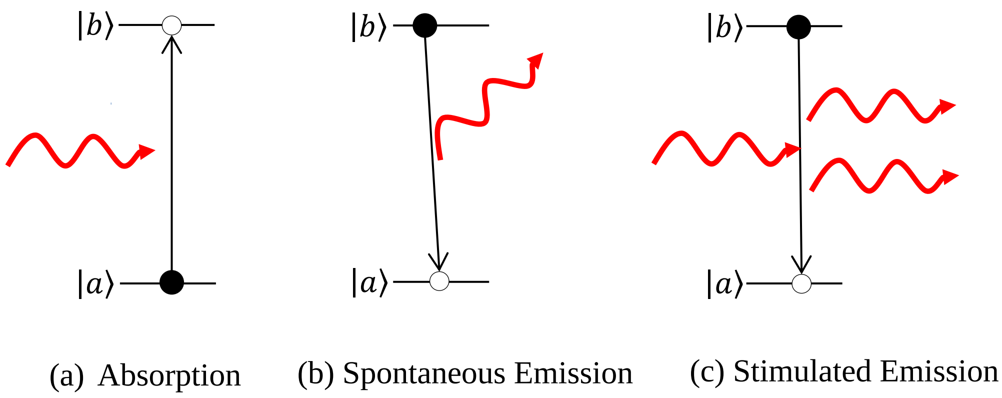

FIG. 2**.** The three ways in which light interacts with an atom: (a) the electron gains the energy of the light in the process of absorption, (b) atom in an excited state decays back down to the initial state emitting a photon during the process of spontaneous emission, (c) while the atom is in the excited state, the atom is subjected to light of equal energy and is promoted to the initial state emitting to photons during the process of stimulated emission.

C. **Absorption and spontaneous emission**

In the previous section, I described what happens when an atom in an excited state is exposed to light with an energy that corresponds to resonant transitions. What is this mechanism that placed the atom in this excited state? There are many different mechanisms that can place an atom into a higher state, but this section focus on the excitation of the atom by electromagnetic radiation. When an atom is in the presence of a polarized monochromatic beam of photons with a frequency that corresponds to certain energy transition $E_{a\to b}$, then an electron in the energy level E_a will absorb the energy of the photon and be excited up to the E_b energy level. It can be said that the atom has absorbed the photon. If after a certain time interval the atom is not exposed to the same coherent light source, the electron in the excited state may spontaneously decay back down to a lower energy state. When this electron begins its transition down, it will emit a photon whose energy is equal to the change in energy of the transition. However, this process is different from stimulated emission because there is only one emitted photon and its direction will be random resulting in incoherent light (Fig. 2).

D. **Quantum notation**

To identify the various states in which an atom may be found, physicists have devised a set of parameters known as quantum numbers. The quantum numbers help to describe certain characteristics of the atom such as spin or angular momentum. All of these quantum numbers follow a set of rules that may be used to determine their value. The most significant number is the principle quantum number, *n*. This quantum number is used to describe the fact that the different energy levels of an atom are quantized to certain values. This number, *n*, may only be an integer number greater than zero and corresponds to the energy level in question. For hydrogen the allowed energies are given by:

$$E_n = -\left[\frac{m}{2\hbar^2}\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\right]\frac{1}{n^2}\,. \tag{6}$$

The motion of an electron that is confined to an atom can be described by orbital motion about the nucleus. As a result of this circular motion, the electron has a specific extrinsic angular momentum $(\vec{\mathrm{L}})$ attached to it as described by the *orbital quantum number*, *l*. Similarly to the allowed energies of the hydrogen atom, the angular momentum of the electron is also quantized. The quantum number, *l*, is used to determine the magnitude of the angular momentum

$$|\vec{\mathrm{L}}| = \sqrt{l(l+1)}\hbar\,. \tag{7}$$

Similarly to the allowed energies of the atom, the angular momentum is also quantized and *l* may take on integer values ranging from 0 up to *n*-1.

The electron also spins about its own axis. The spinning of the electron causes an intrinsic angular momentum referred to as the spin angular momentum $(\vec{S})$ and is described by the *spin quantum number*, *s*. Unlike the principle and orbital quantum number, the spin quantum number is fixed to a value for any given particle. In the case of the electron, the spin quantum number is fixed at $1/2$. The magnitude of the spin angular momentum is given by

$$|\vec{S}| = \sqrt{s(s+1)}\hbar\,. \tag{8}$$

As a result of the spin quantum number being fixed to ½, the magnitudes of the orbital angular momentum and the spin angular momentum are constant. It is also true that the magnitude of the angular momentum is constant for any given value of *l*. If spin orbit coupling is present, the momenta caused by the spin and orbit of the electron interact with each other, causing the components of the two momenta to not be conserved. The interaction between these two momenta couple to form the total angular momentum, $(\vec{J})$, determined by $\vec{J} = \vec{L} + \vec{S}$. The magnitude of the total angular momentum is given by

$$|\vec{J}| = \sqrt{j(j+1)}\hbar, \quad \text{where } j = l+s, l+s-1, \ldots, |l-s|\,. \tag{9}$$

Spin-orbit coupling causes a *splitting* in the energy level, giving new levels labelled by *J*.

E. **Spectroscopic notation**

It is useful to specify the angular momentum of each electron in a multi-electron atom. Frequently that is accomplished by specifying the occupancy of the atomic subshells. Subshells carry over from the states of the hydrogen atom. That is, subshells are specified by l while shells are specified by n. The shells of an atom are labeled with a set of letters that follow the order s, p, d, f,…where s denotes the l=0 , p denotes l=1 and so on. The lithium atom contains three electrons and the shells are filled as follows

$$1s^2 2s^1. \tag{10}$$

This shows that the first $n = 1$ shell is filled and one electron resides in the second subshell. However, this notation does not specify the total angular momentum of the atom. A common way to describe the state of an atom is to use spectroscopic notation with the quantum numbers mentioned previously. Spectroscopic notation allows us to determine more information about the energy levels such as the splitting that is a result of spin-orbit coupling.

$$n^{2s+1}L_j\ , \tag{11}$$

Here, n is the principle quantum number, s is the spin quantum number, L is the total angular momentum and follows the pattern S, P, D, F,…, and J is the total angular momentum quantum number. As in the case of hydrogen, the spin-orbit coupling splits levels and gives rise to fine structure. The splitting's of the $n = 2$ level of lithium are $2P_{3/2}$ ($l = 1$ and $j = \frac{3}{2}$), $2P_{1/2}$ ($l = 1$ and $j = \frac{1}{2}$), and $2S_{1/2}$ ($l = 0$ and $j = \frac{1}{2}$) in order of decreasing energy.[5] The frequency corresponding to the transitions between the different states can be seen in Fig. 3.

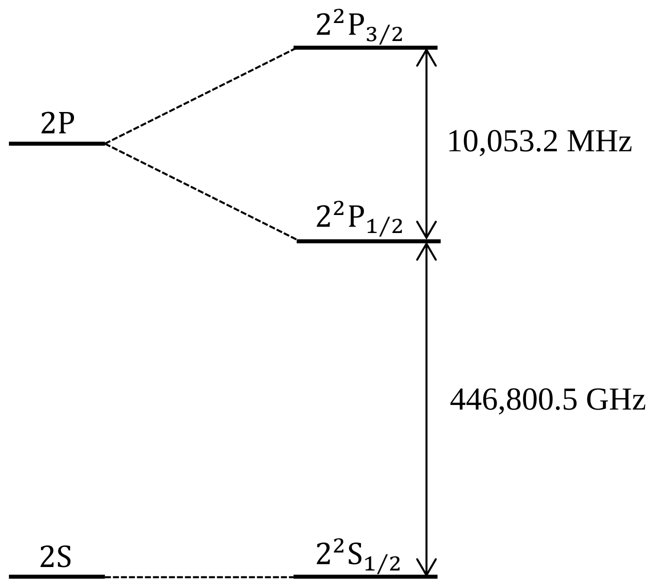

FIG. 3. The fine structure splitting of the $n = 2$ energy level of Li^7 with the appropriate frequency spacing's. Adapted from Peter A. Koenen's thesis.[6]

These transitions correspond to wavelengths of 670.776 nm for the $2^2P_{1/2}$ to $2^2P_{3/2}$ and 670.791 nm for the $2^2P_{1/2}$to $2^2P_{1/2}$ states. The difference between these wavelengths is quite small, so in order to distinguish between them I will need to construct a stable and tunable laser. To achieve this I will implement an *external cavity diode laser* in the Littrow configuration.

IV. LASER

F. Introduction

The most important and central element of this experiment is the laser. It is important to select precisely the frequency at which it operates. This selectivity allows the freedom to choose which energy transition to study. The fundamental element of the laser system is a *diode laser*. Thus, it is imperative to have an understanding of how these devices operate on the fundamental level of the diode.

G. **Band structure**

To understand how a diode functions, it is useful to understand how, in a solid, the loosely bound valence electrons of individual atoms may become detached and are free to "roam" throughout a crystal lattice. These electrons are no longer subjected to the attractive Coulomb force caused by the original nucleus, or parent nucleus, but instead feel a combined potential of all the positive nuclei in the crystal lattice. In crystals, the potential is periodic and can be used to solve the time-independent Schrödinger equation

$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + V(x)\psi = E\psi. \tag{12}$$

Here, ψ is the wave function of the particle in question with no dependence on time. The potential energy of the particle is given by $V(x)$. The energy of the particle is given by E. Following the derivation found in David J. Griffiths *Introduction to Quantum Mechanics*[7] it can be understood that these electrons may only reside in specific energy bands separated by forbidden gaps (Fig. 4). When viewed as solids rather than atoms, the discrete energy levels lose their resolution and become smeared into energy bands.

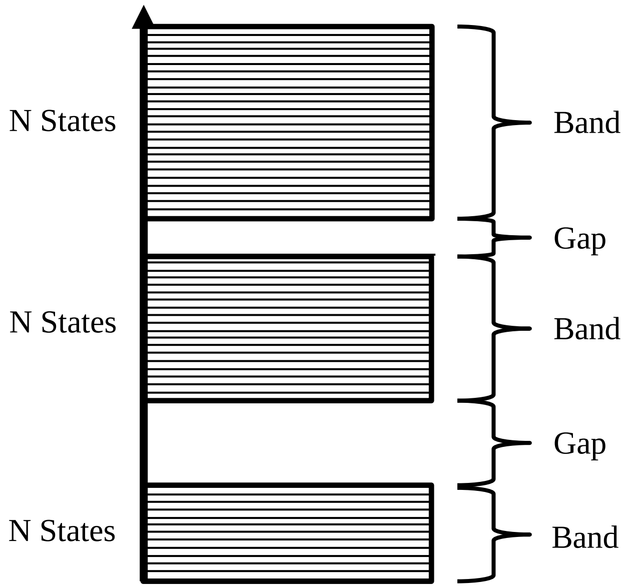

FIG. 4. The allowed energies for a periodic potential form essentially continuous bands.

There are *N* different states within each of these bands and according to the Pauli Exclusion Principle, only two electrons may reside in an individual state.[8] Therefore each of these bands can only hold 2*N* electrons. The number of electrons in a band is given by

$$\#e^{-} = Nq \; . \tag{13}$$

Here, q is the number of free electrons per atom. When $q = 2$, a band will be completely filled and it will take a lot of energy to excite the electron enough so that it may “jump” the forbidden gap. These materials are called insulators (Fig. 5). When $q = 1$, a band will only be half filled and not a lot of energy is needed to excite an electron to another level in the band. These materials are called conductors. Another possibility arises when an insulator is “doped” with atoms containing more or less free electrons than those that make up the crystalline structure. When the insulator is doped with atoms containing more free electrons, extra electrons will be placed into the next higher band allowing for weak electric currents to flow. These are materials are referred to as n-type material. When the insulator is doped with an atom containing fewer free electrons, “holes” will be created by missing electrons in the previously filled band. The resulting material is known as p-type material. This case will also allow for weak electrical currents to flow. These materials are called semiconductors and they are the foundation of how a diode laser operates.

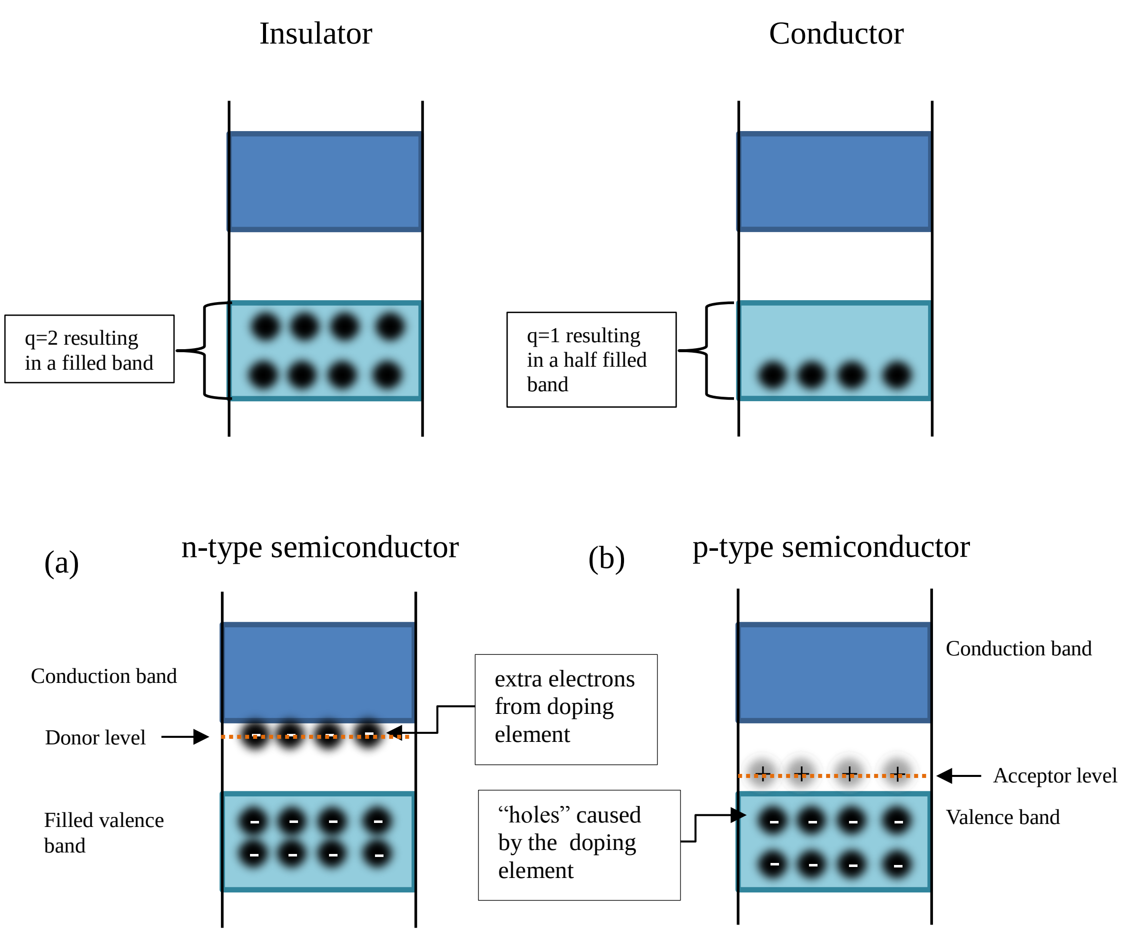

FIG. 5. Diagram demonstrating how electrons fill the bands to create materials with different electrical properties. (a) For an n-type semiconductor, the added free electrons occupy the donor level. (b) The missing electrons, or holes, reside in the acceptor level.

H. **P-N junction**

A diode takes advantage of these properties by stacking an n-type and a p-type semiconductor on top of each other. When this is done, some of the electrons from the n-type material will migrate to the p-type material and resulting in a depletion zone[9] (Fig. 6). This depletion zone will not allow current to flow through the junction unless the p-n junction is forward biased with a voltage creating an internal electric field inside the device. When the applied voltage is strong enough to overcome the depletion zone potential, the positive holes from the p-type material and the extra electrons from the n-type material are both forced into the junction allowing for a current to flow through the device (Fig. 6).

(a) (b) (c)

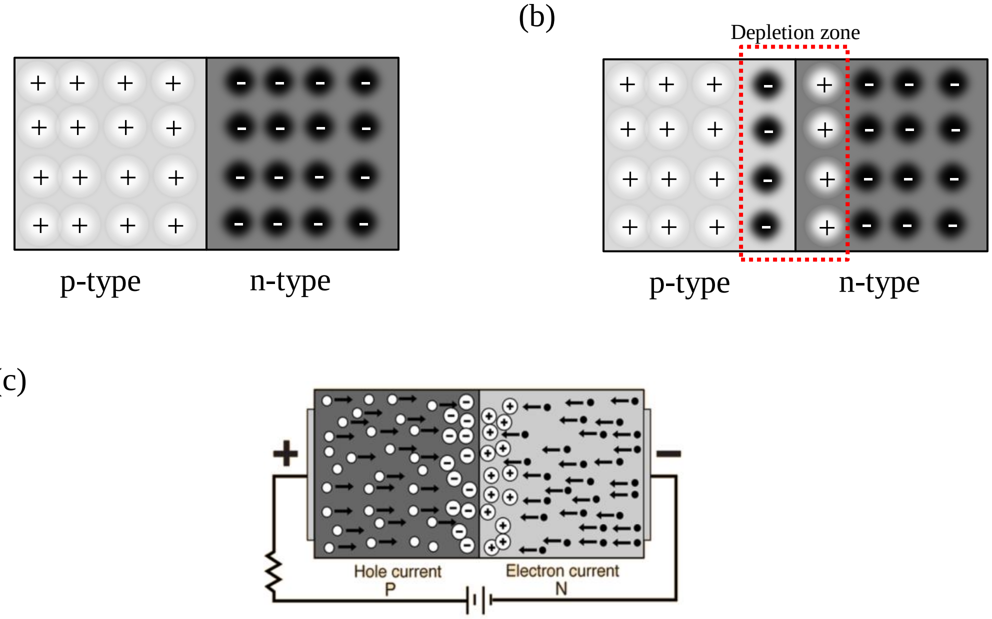

FIG. 6. Depiction of a p-n junction. (a) when initially brought together the n-type material contains the extra electrons and the p-type material contains the holes. (b) After a very short time interval some of the electrons will diffuse into the p-type material establishing a potential difference across the junction known as the depletion zone.[10] (c) When the diode is forward biased the holes and electrons will be forced to the junction eliminating the depletion zone allowing current to flow. Adapted from Hyperphysics.[11]

When the extra free electrons for the n-material combine with the holes from the p-material, photons will be emitted spontaneously.

I. **Population inversion**

Imagine many particles in a system and all of them are promoted to an excited state. Then a photon is introduced, a chain reaction will occur through the stimulated emission mentioned earlier. The incident photon will produce two photons; these two photons will produce 4 photons, and so on resulting in amplification. However, for amplification to occur there needs to be more than half of the electrons to be in the higher energy state or the chain reaction terminates. This requirement is called population inversion (Fig. 7).

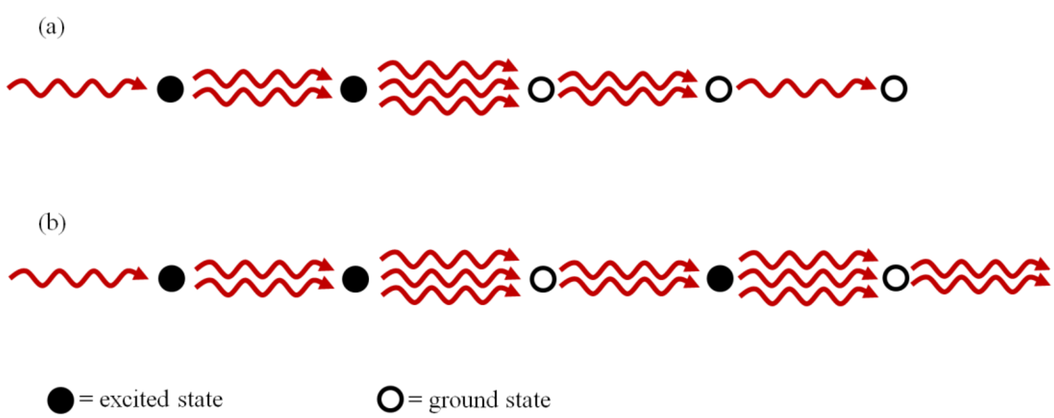

FIG. 7. collection of five atoms (a) with less than half in the excited state producing no amplified light and (b) 3/5 of the population in the excited state demonstrating population inversion and allowing for the amplification of light. More atoms in the excited state will allow for more amplification to occur.

J. **Laser operation**

Diode lasers take advantage of both stimulated emission and the combination of p and n-type materials to produce an amplified signal. To achieve stimulated emission, population inversion and a feedback system must be established. Figure 8 represents a model of a typical diode laser where the two ends have reflective properties providing the feedback to the system. One of these faces typically has a reflectivity of 100% and the other face will allow some light to be emitted and some to be reflected, providing the feedback as well as an output signal.

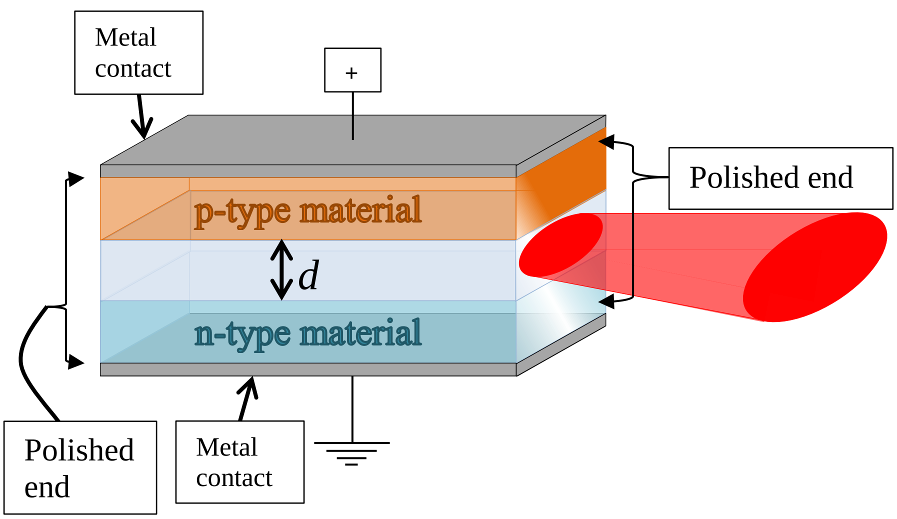

FIG. 8. A simple diagram of a p-n junction diode laser where the active region is represented by *d*. This active region acts as the gain medium and the polished end provides the feedback for the system

While this operation is suitable for most situations, our experiment requires very precise selection and tuning of the output wavelength in order to select the transitions of interest. A special modification of the diode laser helps achieve this known as an *anti-reflection coating.*

K. **Anti-Reflection coating**

To help reduce the possibility of competing modes within the laser system, an anti-reflection coating has been applied by Sacher-Lasertechnik to bring the reflectivity of the output facet close to zero. One of the most commonly used methods is the deposition of a dielectric anti-reflection (AR) coating by single layer.[12] The material needed for coating can be determined by its index of refraction

$$n_f = \sqrt{n_o n_s}\,, \tag{14}$$

and thickness

$$t = \frac{\lambda}{4}. \tag{15}$$

Here, n_f is the index of refraction of the layer, n_0 is the index of refraction for air, and n_s is the index of refraction of the substrate. When the thickness of the coating reaches a quarter the wavelength the diode will not act as a laser. The coating is taking advantage of thin films and destructive interference to eliminate the reflected waves. When the thickness of the film is a quarter of the wavelength, the transmitted light from the first surface must travel a greater distance. When the light reflects off of the rear surface it experiences a 180 degree phase shift. Now, a peak from the first light ray is aligned with a trough of the reflected ray from the second surface, thus optically cancelling out.

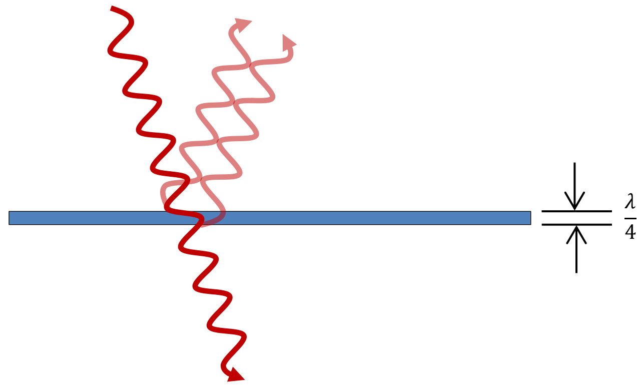

FIG. 9. Representation of destructive interference caused by a thin film of thickness $\frac{\lambda}{4}$. In this diagram it is easy to see how the reflected ray from second surface is 90 degrees out of phase with respect to the reflected ray from the first surface. These two rays will destructively interfere providing no reflection.

This coating on one side of the diode chip stops the device from lasing. It still emits light, but it is the incoherent light of a light emitting diode. The way in which the laser is recovered is shown in section V C.

V. APPARATUS

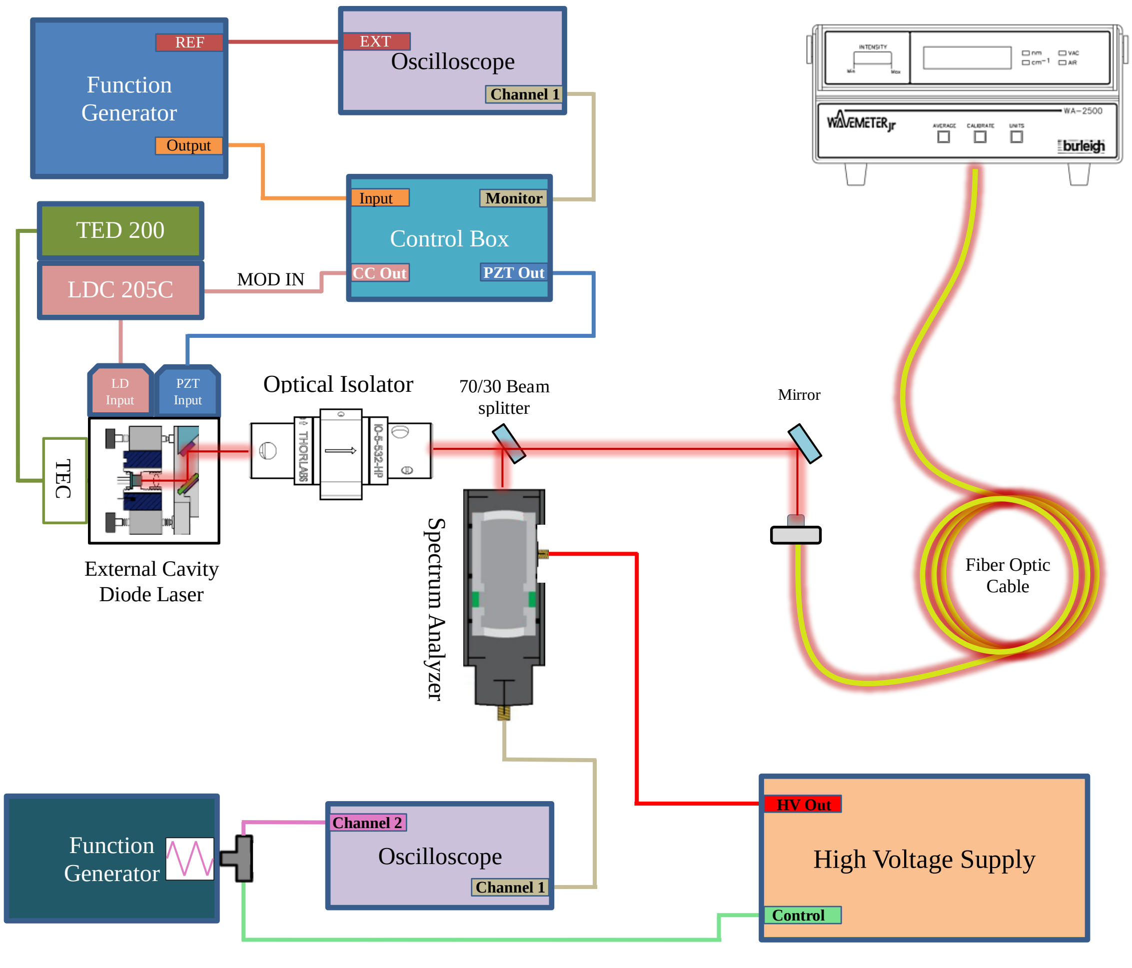

FIG. 10. Diagram of the apparatus.

L. Laser diode

The laser implemented in our experiment is an anti-reflection coated semiconductor laser diode from Sacher-lasertecnik model SAL-0670-20 with a peak operating wavelength of 667.1 nm as seen in Fig. 11.

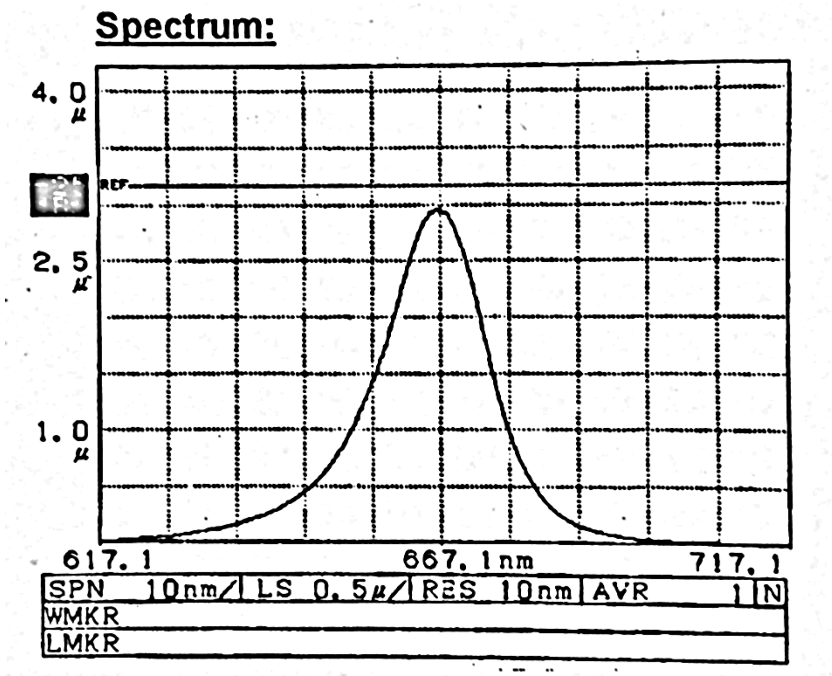

FIG. 11. The spectrum of the laser diode used in the experiment that has a peak operating wavelength situated at 667.1 nm.

This laser diode is well suited for our application because the peak operating wavelength corresponds closely to wavelength needed to excite a lithium atom. So far, I have only seen a fraction of the output power quoted by the supplier: 3.2 mW compared to the given 20 mW. This maximum output power of 3.2 mW was achieved when the laser was operating at a wavelength of 667 nm, which corresponds to the peak Fig. 11. As the laser was being tuned to 670.8 nm it was observed that the output power dropped significantly. As the laser is tuned, it must follow the line on the emission spectrum, so some power drop is expected.

M. **External cavity diode laser**

As mentioned above, the laser cavity within the chip is destroyed by an antireflection coating one surface of the laser chip. A new laser cavity, which greater wavelength selectivity, is formed by elements outside of the chip. The arrangement is shown in Fig.12.

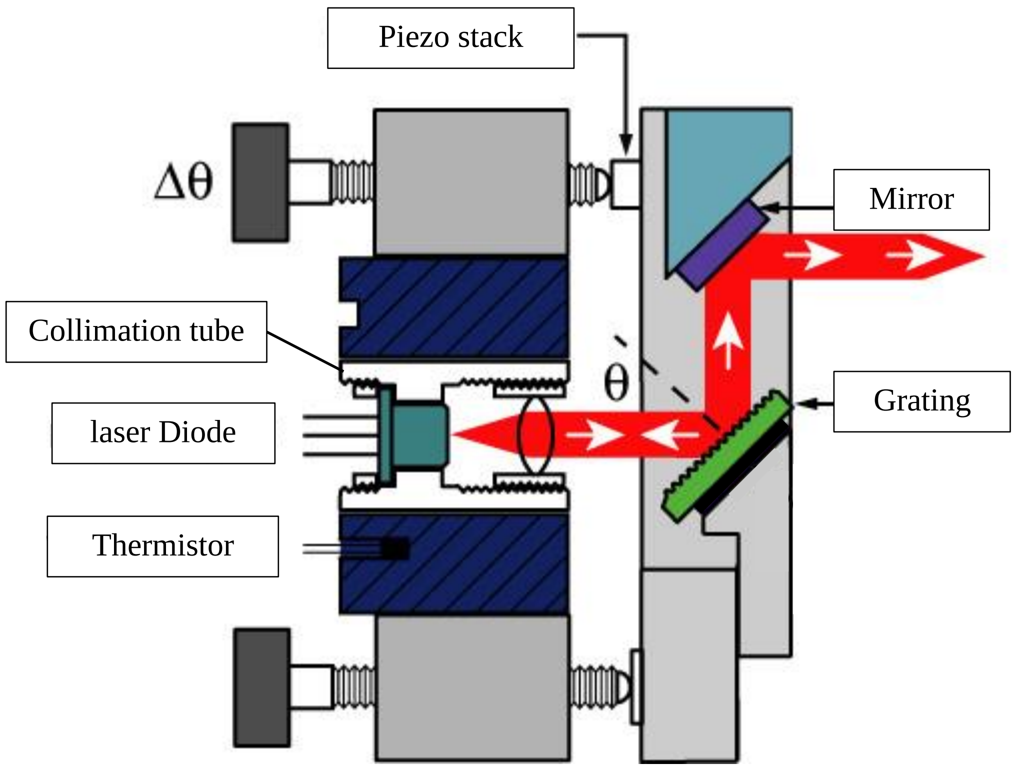

FIG. 12. An external cavity arrangement with a mirror affixed to the moving arm to provide a fixed output beam. Adapted from the University of Melbourne.[13]

The diffraction grating is essential to this configuration because it provides the feedback to the laser diode chip as well as the output beam. Without this diffraction grating, the diode will only spontaneously emit light and lasing cannot be achieved.

N. **Collimation**

For the ECDL to be as efficient as possible, it is important to collimate the light being emitted from the diode into a parallel beam. In fact, it was noticed that if the beam was not properly collimated, the diode would not lase. Proper collimation occurs approximately when the focal point of the lens coincides with the output facet of the diode chip (Fig. 13).

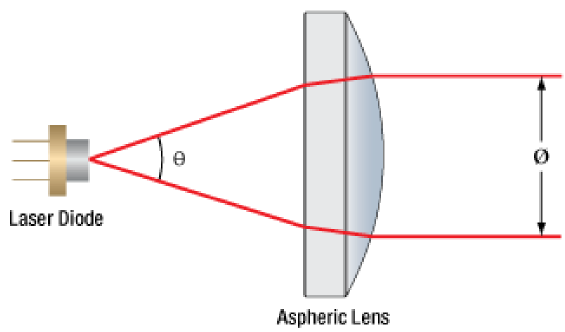

FIG. 13. Diagram representing the collimation of the light emitted from the laser diode. The angle theta, θ, represents the beam divergence emitted from the diode and phi, $\emptyset$, represents the diameter of the output beam.

The most efficient way that to check the collimation of the beam is to direct the beam at a spot a significant distance away from the source. This allowed a greater distance for the beam to diverge a significant amount and the lens could be positioned accordingly. The collimation tubes used in our apparatus are from ThorLabs and each was designed to hold a collimating lens. I tried several collimation lenses, each with a different focal length: 4.5mm, 6.24 mm, 8.0mm, and 11.0 mm. However, when the laser diode was mounted in the collimation tube with the 4.5 mm focal length lens, it was noticed that as the lens was displaced too far from the diode chip, the range of travel was not enough to allow the beam to be properly collimated. The next step was to attempt collimation with the various other tubes and lenses, but collimation could not be achieved with the available lenses. From this I was able to gather that the dimensions of the laser diode were not appropriate for the collimation tubes.

Lenses with such short focal lengths might touch the diode chip, which would likely damage the device. As a result, care should be taken when attempting to collimate the beam. It has been observed that when the collimating tube is rotated, the output beam will also be displaced by a significant amount, suggesting the diode emission is not collinear with the axis of the lens. This could contribute to the diminished output power.

I attempted to combine various lenses with different collimation tubes as a means to achieve collimation. However, I was unable to collimate the beam using this approach. I designed a new collimation tube to be constructed by the science-shop machinist, Aco Petrusevski. Before the design began, it was important to check the beam divergence so that the appropriate lens could be chosen to maximize the performance. The beam divergence was not provided by the manufacturer, so this had to be done manually. After very carefully supporting the laser diode outside of the collimation tube, the power was turned on revealing a rather large beam divergence. I then decided that the smallest focal length lens should be used in an attempt to capture as much light as possible. The 4.5 mm focal length lens was chosen and I designed the collimation tube around the lens using the specification sheets provided from ThorLabs. The exact size of the post supporting the laser diode chip is not known so the distance was approximated using digital calipers. Using this distance, I designed the tube to hold the lens 4.5 mm from the diode and allowed for a range of motion of ± 2 mm. This resulted in proper collimation of the beam. Unfortunately, the issue of the beam being displaced as the tube is rotated was still present.

O. **Diffraction grating**

After the beam was collimated, the next step was to implement a diffraction grating into the ECDL. The diffraction grating is essential to the operation of the laser because it provides the positive feedback needed to achieve stimulated emission.

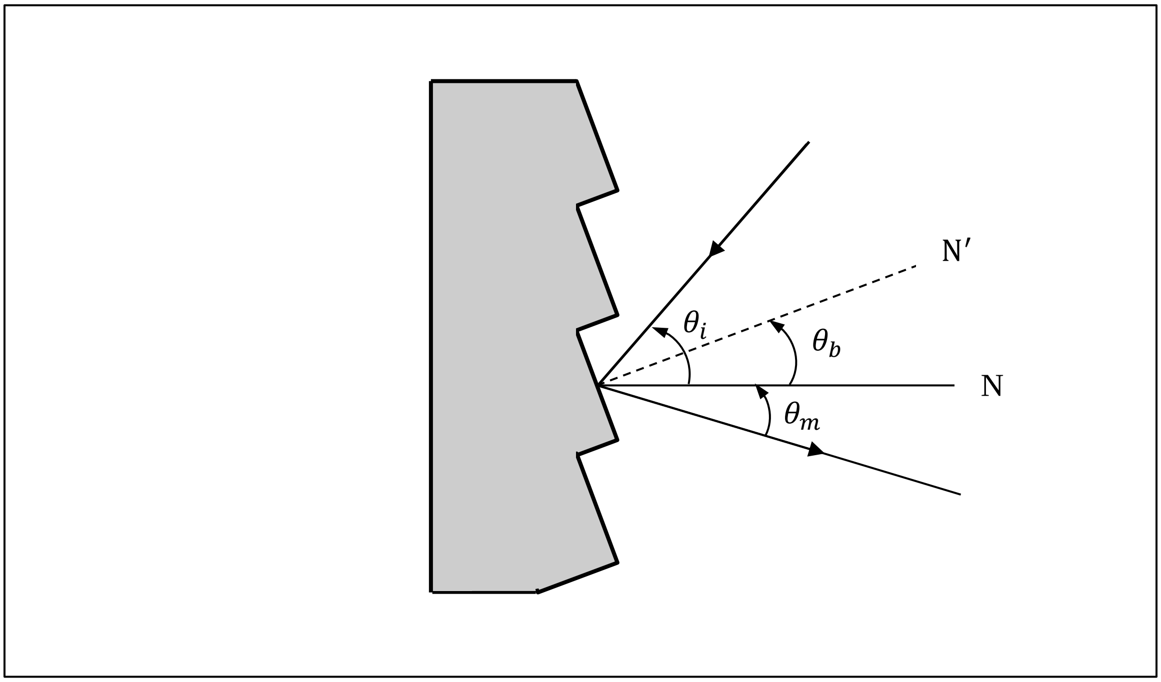

FIG. 14. Schematic of a diffraction grating. The incident ray comes in at an angle θ_i to the normal, N, the reflected ray exits at an angle θ_m to the normal. θ_b is the blaze angle and d is the spacing between ridges.

The angle at which the grating should be mounted can be derived from the grating equation[14]

$$d(\sin\theta_i + \sin\theta_m) = m\lambda\,, \tag{16}$$

here, d is the lines per millimeter, θ_i is the angle of incidence from the normal, θ_m is the angle the reflected ray makes to the normal, λ is the wavelength of incident light, and m is the diffraction order. For an ECDL in the Littrow configuration, the first order reflection is directed back into the collimation tube to provide the positive feedback. This simplifies the grating equation to

$$m\lambda = 2d \sin \theta. \quad (17)$$

To excite lithium, the laser needs to be tuned to approximately 670 nanometers and this corresponds to an angle of 37.15 degrees. When the diffraction grating is aligned properly, the first order diffraction will provide the feedback and thus extend the cavity length. The diffraction grating is mounted onto an arm that can be adjusted as a way to tune the output frequency.

1. Coarse frequency tuning

The advantage of using an ECDL is that it allows us to control the length of the cavity so that the output wavelength can be adjusted. There are two different parameters of the grating that need to be considered while tuning the ECDL. The two methods of grating adjustment involve changing the length of the cavity by adjusting the two screws as seen in Fig. 15.

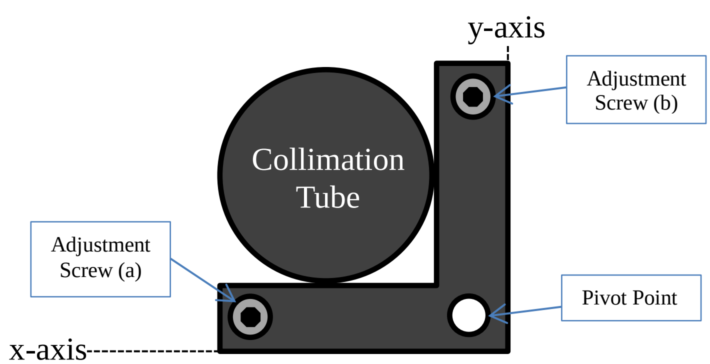

FIG. 15. Diagram representing the side of the ECDL apparatus facing the operator. The grating is fixed to an adjustable L shaped arm located on the opposite side of the L shaped base arm. The two adjustment screws will change the angle of the adjustable arm about the pivot point. Adjusting screw (a) results in an angle change from the x axis, θ, and adjusting screw (b) results in an angle change from the y-axis, ϕ.

I expect that screw (a) is the most important adjustment for wavelength, and screw (b) is the most important feedback adjustment. These controls are not completely independent, however. Adjusting both screws in an iterative fashion is required to give the best power at the desired wavelength. If the angle θ is continuously adjusted without tweaking the angle ϕ then the output wavelength will jump erratically. It was convenient to have an estimate of how many rotations of screw (a) would be needed to reach 670.8 nm from the peak output of 667 nm. To do this, an understanding how the adjustment arm is affected by small adjustments of screw (a) was needed (Fig. 16).

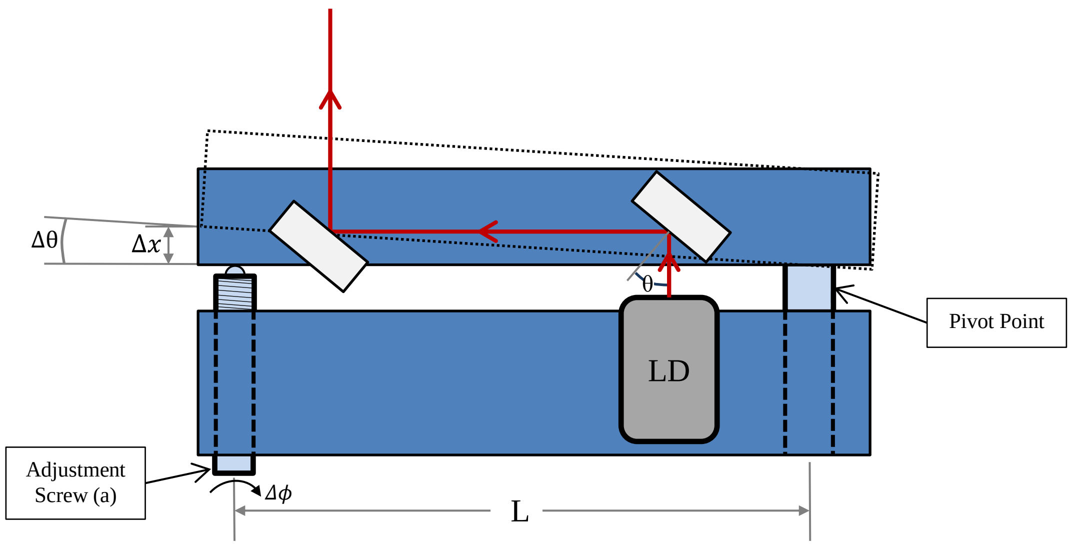

FIG. 16. Diagram representing the small displacement achieved by slowly rotating the screw (a).

Starting with the simplified grating equation (17), I can determine the change in wavelength to be

$$\Delta\lambda = \frac{d\lambda}{d\theta}\Delta\theta\,. \tag{18}$$

Solving for Δθ and then applying the derivative yields

$$\Delta\theta = \frac{\Delta\lambda}{2d\cos(\theta)}\,. \tag{19}$$

Now that the amount the angle needs to be change is known, it will be useful to determine approximately how many times the screw will need to be rotated. I know that the distance the screw displaces the arm, Δx, is equal to the threads per inch, p, times the change in angle of the screw, $\Delta\phi$,

$$\Delta x = \frac{\Delta\phi}{p}. \tag{20}$$

I also know for small angle displacements

$$\Delta x = l\Delta\theta. \tag{21}$$

Solving equation (20) for $\Delta\phi$ and substituting equation (21) for Δx and equation (19) for $\Delta\theta$ reveals

$$\Delta\phi = lp\frac{\Delta\lambda}{2d\cos(\theta)}. \tag{22}$$

For our apparatus, p is equal to 80 $\frac{\text{threads}}{\text{inch}}$, l is approximately equal to 1.53 inches, and $\Delta\lambda = 4$ nm. Substituting these values into equation (22) suggests that I will need to turn the screw approximately 0.55 times. This corresponds to a change in wavelength of 1 nm for every 0.14 rotations.

2. Fine frequency tuning

Once the ECDL is tuned to the proper wavelength using the course adjustment, the next step is to add fine adjustment of the cavity length. The fine adjustment is essential for scanning the frequency of the laser system. The level of precision needed for scanning the frequencies cannot be achieved by hand so a piezoelectric stack (ThorLabs AE0505D08) is placed between the tip of the screw and the adjustment arm. The piezoelectric transducer (PZT) will expand or contract depending on the voltage applied to it, and for this piezoelectric element the recommended drive voltage is 100 V corresponding to a displacement of 6.1 ± 1.5 μm. Using equations (21) and (19) I can determine that the maximum change in wavelength of the laser to be

$$\Delta\lambda = \frac{\Delta x}{l} 2d\cos(\theta)\,, \tag{23}$$

and by using the relation

$$\nu = \frac{c}{\lambda}, \tag{24}$$

the approximate change in frequency can be determined

$$\Delta\nu = -\frac{c}{\lambda^2}\frac{\Delta x}{l} 2d\cos(\theta). \tag{25}$$

where, $l = 38{,}100$ µm, $\lambda = 670.8$ nm, $\Delta x = 6.1$ µm, c is the speed of light, and $\theta = 37.15°$. These values correspond to a frequency range of approximately 92 GHz while scanning the laser. This is equivalent to 920 MHz/ V.

3. Control box

Sweeping through frequencies requires a voltage ramp for the piezo element as well as the current controller. This required the construction of an external controller box that will allow the voltage to the piezo element and the current controller by independently adjusting the dc offset and gain for both channels. Fig. 17 contains the schematic of the circuit used.

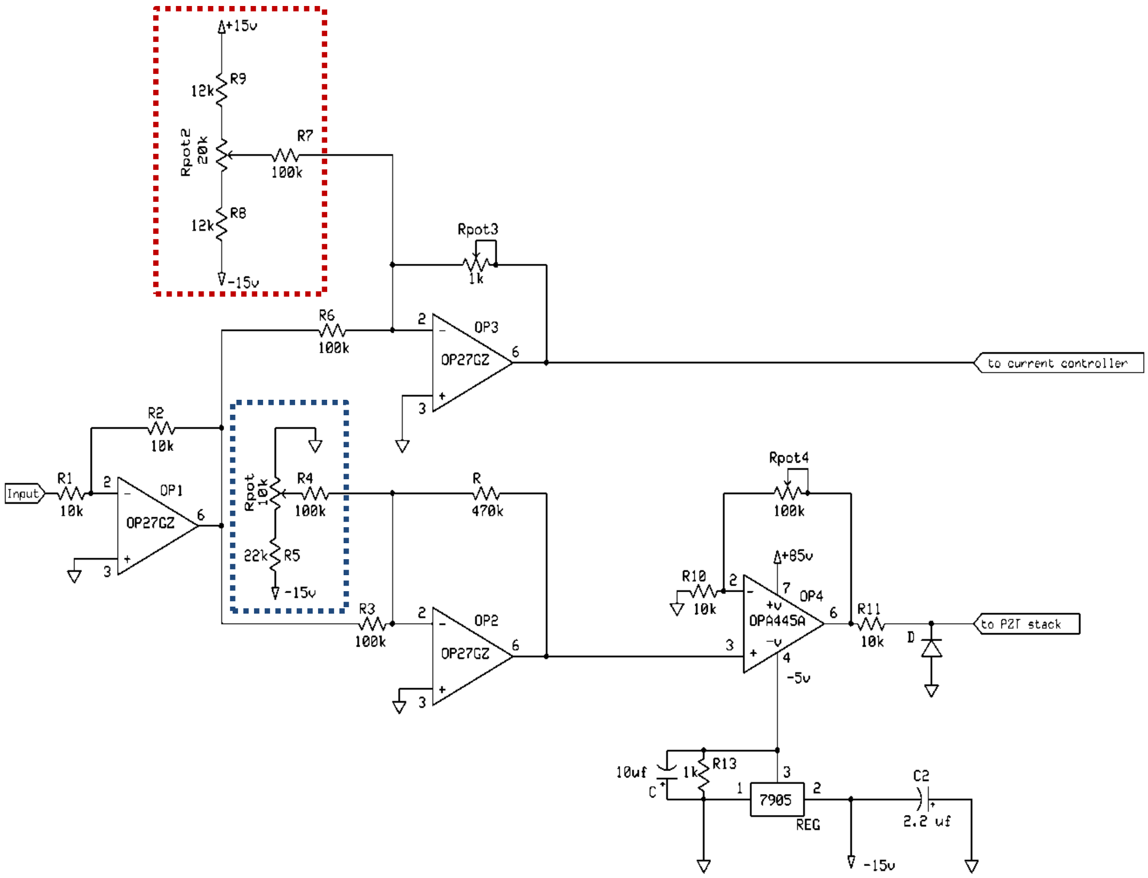

FIG. 17**.** A schematic of the control box circuit used to ramp the voltage and current while providing individual gain and bias control of each waveform.

The circuit in Fig. 17 consists of three standard amplifiers configured as inverting amplifiers each labeled OP1, OP2, and OP3 and a fourth high-voltage amplifier to provide the output for the PZT. A triangular waveform from an SRS function generator Model DS345 is sent into OP1's inverting input where it experiences a gain of -1 according to

$$G = -\frac{\mathrm{R2}}{\mathrm{R1}}. \tag{26}$$

The output of OP1 is then fed into OP3 and OP2 where the gain of their output is determined by

$$G_{\mathrm{OP3}} = -\frac{\mathrm{R_{pot}3}}{\mathrm{R6}}, \tag{27}$$

$$G_{\mathrm{OP2}} = -\frac{\mathrm{R}}{\mathrm{R3}}, \tag{28}$$

once again inverting the input signal of their respected inputs. The portion of the circuit indicated by the red dotted box is an adder circuit used to adjust the dc offset of the current controller (CC) output. The amplitude of the CC output can be adjusted with the 1 kΩ potentiometer labeled $\mathrm{R_{pot}3}$. It was observed that the value of the gain may never exceed 0.01, corresponding to a much lower output voltage. This value was determined using the external analog modulation equation found in the ThorLabs LDC200C series operation manual

$$\mathrm{I_{LD}} = \mathrm{I_{LD\ SET}} + \frac{\mathrm{I_{LD\ MAX}}}{10\ \mathrm{V}} * \mathrm{V_{MOD}}\,. \tag{29}$$

Where, $\mathrm{I_{LD\ MAX}} = 500$ mA for the LDC205C model, $\mathrm{I_{LD\ SET}}$ is the constant current setting determined by the user, $\mathrm{V_{MOD}}$ is the input voltage into the MOD input of the LDC205C, and $\mathrm{I_{LD}}$ is the current sent to the laser diode. From this equation it can see that only a small modulation amplitude is needed to change the output current by a significant amount, so it is crucial to keep the output of OP3 on the order of a millivolts. For our particular arrangement, an input signal of 6 $\mathrm{V_{pp}}$ corresponds to a maximum OP3 output of approximately 130 mV. This will provide us with a current swing of approximately 6 mA which is plenty for our application. Note: The panel reading of the SRS DS345 estimates the output voltage into a 50 OMEGA load. The actual output voltage delivered to the control box (a high-resistance load) is about twice as large.

It is important to understand how much the frequency shifts for a given amount of current (Fig. 18).

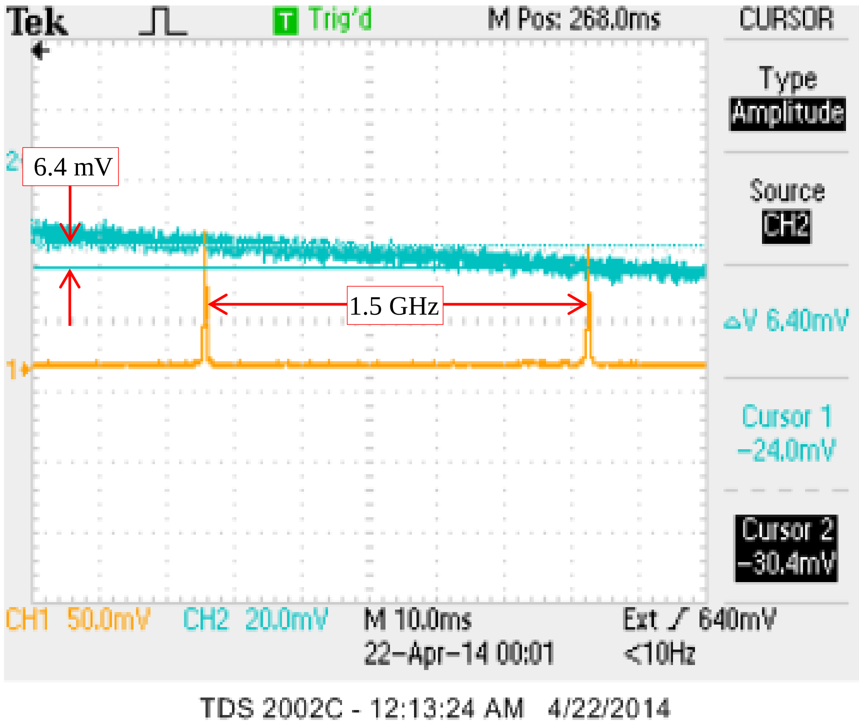

FIG. 18. Oscilloscope data of the control current output and the peaks detected by the spectrum analyzer. The averaging function was turned on and set to 4 to reduce the noise of channel 2.

From the oscilloscope data I was able to determine that a change of 6.4mV corresponds to a shift in frequency of 1.5 GHz. This corresponds to a shift of 234.4 MHz per mV. It is useful to understand how this relates to the current going to the LD. Using equation (29) and a set diode current of 106.0 mV I can determine that a 1 mV change in the current control output corresponds to 0.05 mA change in the current.

The portion of the circuit outlined by the red dotted box is an adder circuit responsible for the DC offset of the CC output signal. This particular adder circuit cleverly uses a potentiometer as a voltage divider to adjust the amount of voltage to be added to the output. When the value of the potentiometer is set to exactly 10 kΩ, the added voltage will be zero. By adjusting the dial on $R_{pot}2$, the amount of voltage added to the CC output can be adjusted. The equation that determines the output of OP3 is

$$V_{out}OP2 = -\frac{R_{pot}3}{R6} * V_{OP1\ output} - \frac{R_{pot}3}{R7} * V_{divider\ output}\ . \qquad (30)$$

Where, $V_{divider\ output}$ refers to the output voltage from the potentiometer. The offset added to the circuit determines how far from zero the center of the output waveform is located. This plays a significant role when maximizing the scanning capabilities, discussed in later sections. In contrast to OP3, the gain of OP2 was originally chosen to produce a much larger output voltage by setting $R = 470\ k\Omega$ and $R3 = 100\ k\Omega$ providing a gain of approximately 5. However, this was found to be overdriving the input of the fourth operational amplifier so a more conservative value of 100 kΩ was chosen for R, resulting in a gain of -1. The elements of the circuit indicated by the blue dotted box are responsible for the DC offset of the PZT voltage. It is important to note that any negative voltages applied to the PZT device will destroy the device. Because negative voltages are not needed, the OP2 adder circuit positive supply is connected to ground so that only negative voltages are added to the signal. With a gain of -1, this corresponds to positive DC offset. It is extremely important to realize that this does not provide any protection from negative voltages for the PZT stack! Some protection is provided by the diode on the output of the fourth operational amplifier. However, the protection diode does not become active until -0.6 V is applied to it, so it is still necessary to monitor the output with an oscilloscope. To monitor the output a voltage divider is used by using a 9 MΩ resistor in series with the 1MΩ internal resistance of the oscilloscope to divide the output by 10. However, the resistor values limit the accuracy of the voltage divider. The fourth operation amplifier is configured as a non-inverting amplifier with a gain of

$$G = 1 + \frac{R_{pot}4}{R_{10}}. \tag{31}$$

Where, $R_{pot}4$ is a potentiometer with a maximum value of 100 kΩ and R_{10} is a 10 kΩ resistor corresponding to a maximum gain of 11. The OP4 amplifier is powered by +85 V and -5 V limiting the output of OP4 to approximately 90 V safely driving the PZT stack. It was observed that the output amplitude going to the PZT stack never reached the desired 90 volts but instead appeared to peak at 82 V (Fig. 19). Two possible reasons for this are as follows: the attenuation of the voltage divider is not precisely 10, and the gains of the op-amps may not as expected. These problems may arrive from using common 5% tolerance resistors.

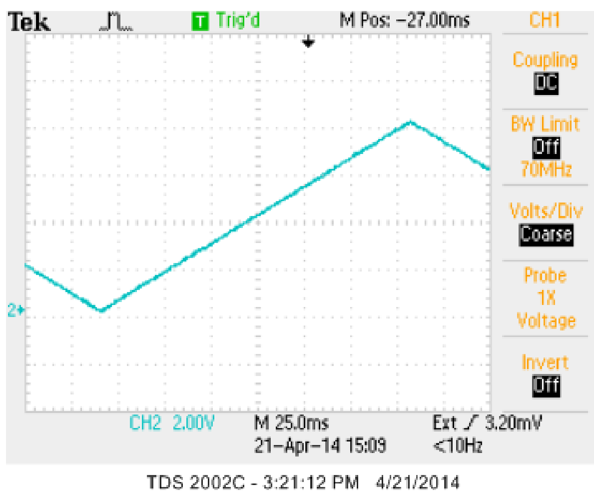

FIG. 19. Screen shot from the oscilloscope representing the maximum voltage that can be supplied to the PZT stack from the control box.

Now that the output of the control box is understood, it is useful to estimate how much the PZT stack will displace the arm. To do this I will assume the displacement of the PZT stack is a linear function of voltage to estimate the displacement at 82 V (Fig. 20).

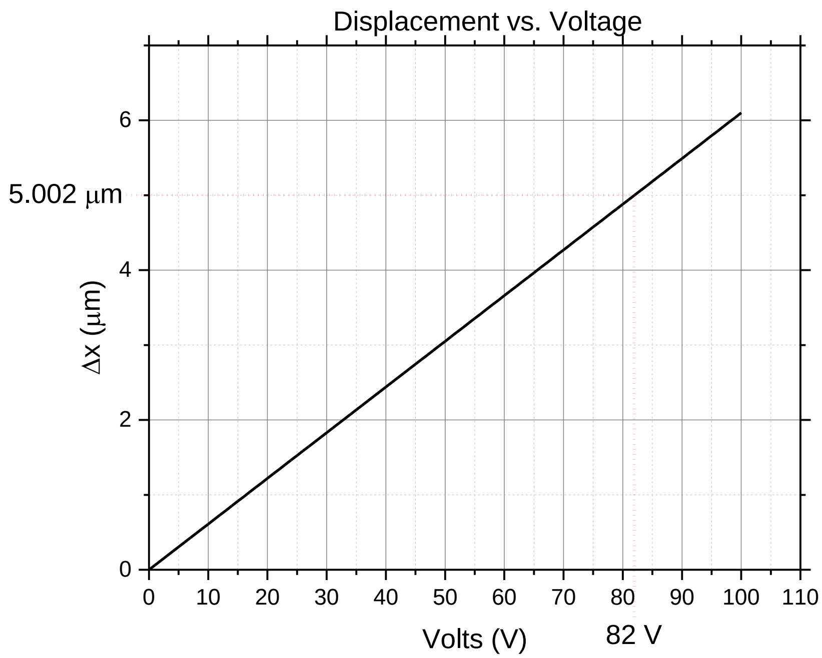

FIG. 20**.** Plot of Displacement vs. Voltage for the PZT stack. This is assuming a linear relationship between the applied voltage and displacement.

Figure 20 reveals that at our actual applied voltage of 82 V results in a displacement of approximately 5 μm. Using this new displacement value I found that for every one volt I should see a frequency change of 750 MHz. To test the accuracy of our calculation the high voltage sweep going to the spectrum analyzer is shut off to prevent it from scanning. While the laser is sweeping, the PZT output and the output from the spectrum analyzer are fed into an oscilloscope (Fig. 21).

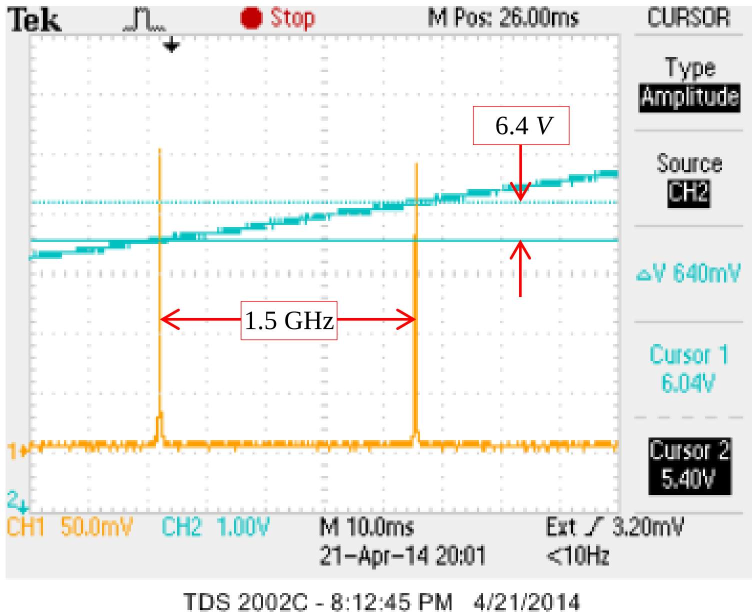

FIG. 21. Oscilloscope data revealing a frequency shift of 1.5 GHz for every 6.4 *V.*

This data reveals a frequency shift of 234.4 MHz per volt. This result is surprisingly different from the calculated value. Some possible sources of error could be caused by the PZT's ability to respond to different loads. If the load applied by the spring clamping the adjustment arm against the PZT is too strong, the PZT stack may not expand to the full 5 µm as expected. Also, it is possible that a different model PZT stack is in this ECDL, with a different displacement. The other PZT stack in question has a displacement of 3.0 µm at 100 V corresponding to 2.46 µm at 82 V. Replacing this value for the 5.0 µm reveals a frequency shift of 374 MHz per volt. This however, is not very likely and the load on the PZT stack is the best explanation for the discrepancy.

4. Control box tuning

The control box is using an input signal from the SRS function generator to produce two different voltage outputs. Each of these parameters determines the frequency at which the laser operates. It is important to calibrate these outputs so that they both determine the operating frequency in unison. This concept can be understood by observing the connections between the control box, PZT stack, and the laser diode through a block diagram (Fig. 22).

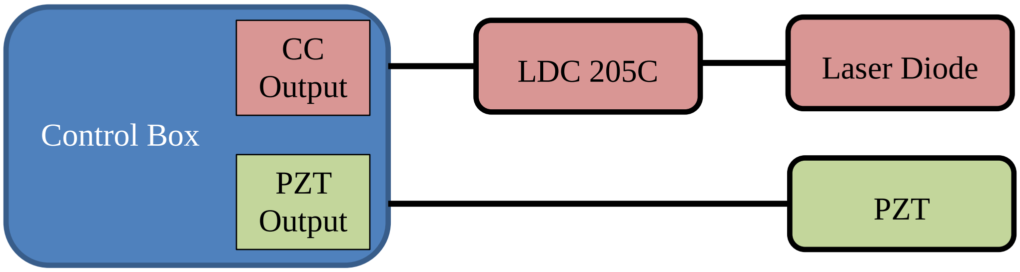

FIG. 22. Block diagram representing the connections from the Control box to each outputs respective device.

As the PZT output voltage is increased, the PZT stack expands approximately with the output voltage ultimately resulting in a displacement of the grating. When the grating itself is displaced, it expands the cavity resulting in a new output frequency of the laser system. It is easiest to understand this relation through a diagram as seen in Fig. 23.

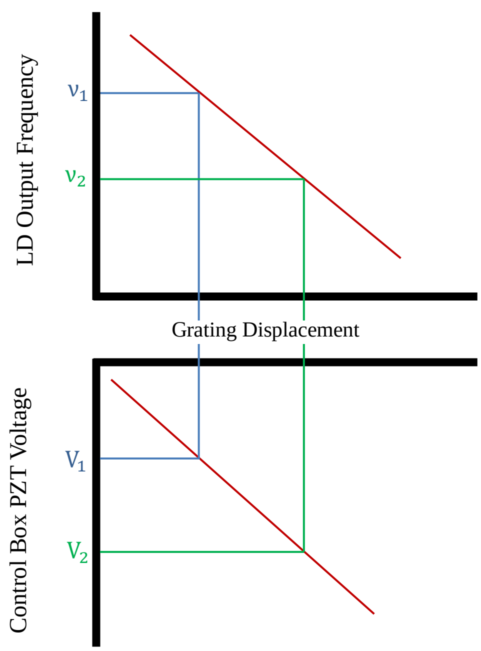

FIG. 23. Diagram representing how increasing the voltage to the PZT stack will lengthen the external cavity resulting in a decrease in the frequency.

If the voltage to the PZT stack is increased from V_1 to V_2, the output frequency will decrease from ν_1 to ν_2. Now if we examine the connections made from the control box to the LD, we see that there is an intermittent step involving the LDC 205C to convert the voltage from the CC output to a current for the LD, further complicating the process.

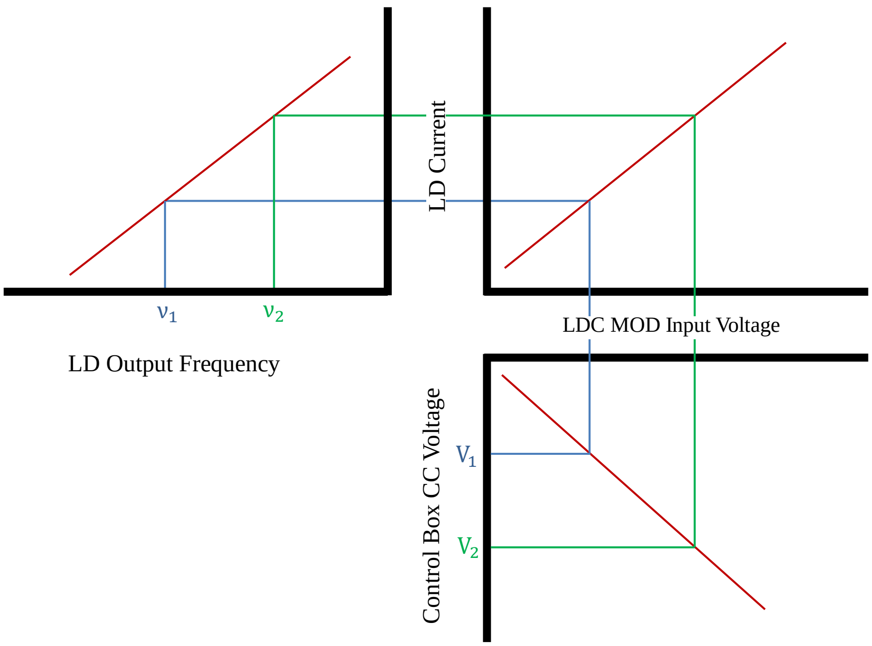

FIG. 24. Diagram representing how an increase in the control box CC output voltage from will ultimately decrease the output frequency of the laser diode.

As seen in Fig. 24, if the voltage from the control box is increased from V_1 to V_2 then the output frequency of the laser will decrease from ν_1 to ν_2. It can be gathered from both Fig. 23 and Fig. 24 that the CC and PZT output of the control box can result in different operating frequencies of the laser system. The operating frequency of the laser can be monitored using a spectrum analyzer, discussed in the section G. The spectrum analyzer allows the determination that the output of the laser is indeed a single frequency, indicated by a single sharp peak seen on an oscilloscope. As the frequencies are scanned, the peak will scan through the free spectral ranges of the spectrum analyzer. The purpose of the control box is to ensure that as a range of frequencies are scanned the laser diode will continue to operate in a single frequency mode. If the settings of the control box are not set correctly, erratic behavior in the output frequency of the laser can be observed. To ensure that the laser will operate in a single mode throughout the entirety of the scan, both the curves in the LD current vs. output frequency and the grating displacement vs. output frequency need to be aligned on top of each other (Fig. 25).

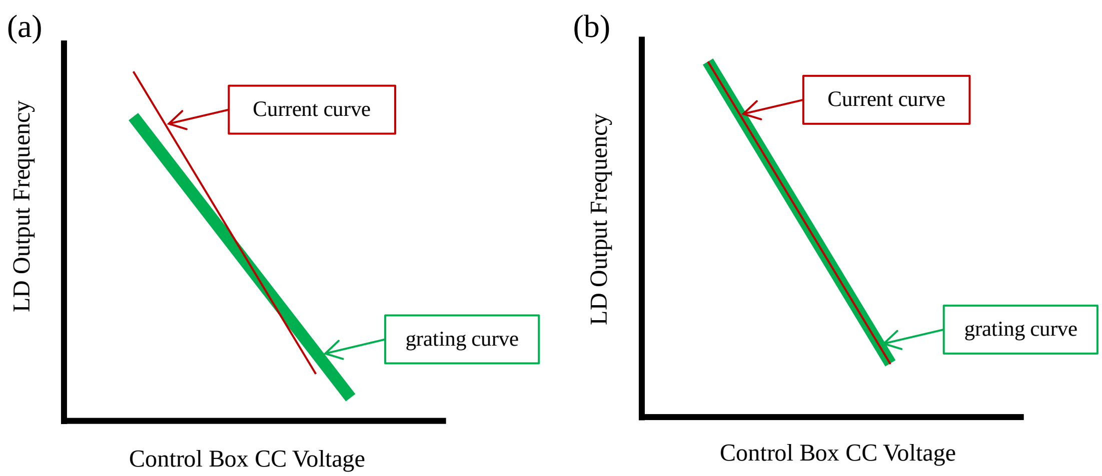

FIG. 25. Diagram relating the output frequency curves of both the grating adjustments and the current adjustments. (a) Represents a relationship between the two where erratic behavior of the laser will be seen and both the bias (offset) and the gain (slope) of each curve will need to be adjusted. (b) Represents a situation where both the outputs will sweep through the frequencies in unison and no adjustment is needed. The output of the spectrum analyzer will display single mode operation during the sweeps.

This is done by adjusting the slope (gain) and the offset (bias) until the output displays continuous single mode operation throughout the scan.

P. Laser diode current controller

In order to maintain stable operation of the diode, current noise must be eliminated to ensure precise control of the current. It is also very important to set a current limit to protect the diode. This is achieved using a ThorLabs laser diode controller model LDC205. This controller is very important because it provides a very stable current output as well as the ability to set a current limit to ensure that safe operation of the diode is always maintained. The laser diode is connected directly to the LDC via a 9 pin CAB400 cable. The connections are described in Fig. 26.

CAB400 (9 Pin Male)	PIN #	
	1	Interlock and Status LASER ON/OFF
	2	Photodiode[a]
	3	Laser Diode Ground
	4	Photodiode[b]
	5	Ground for Pin 1
	6	Voltage Measurement Laser Diode Cathode[c]
	7	Laser Diode Cathode (with Polarity Anode Grounded - AG)
	8	Laser Diode Anode (with Polarity Cathode Grounded - CG)
	9	Voltage Measurement Laser Diode Anode[c]

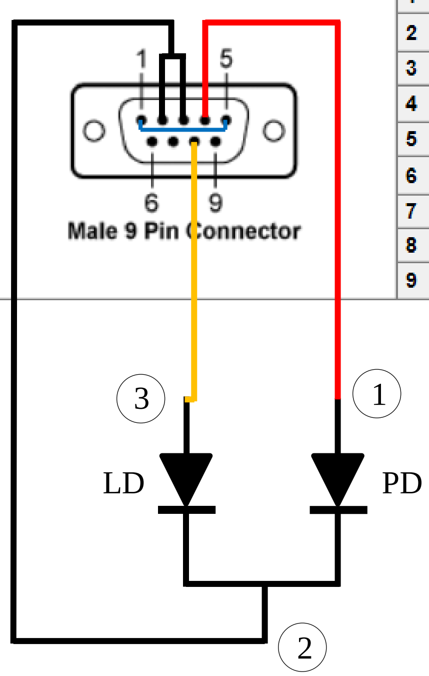

FIG. 26. Schematic of the connections for the laser diode. PD represents the photodiode used to determine the output power and LD represents the laser diode. The laser diode anode is connected to pin 8, the photodiode anode is connected to pin 4, and the common cathode is connected to pins 2 and 3 for ground. Pin diagram adapted from ThorLabs schematic.

A reliable and steady current source is crucial for fine tuning the output frequency of the laser diode. For reasons that are somewhat obscure, the wavelength increases as the laser diode current increases.

Q. Temperature controller

The temperature of the laser diode must also be maintained. This is achieved by implementing a Peltier thermoelectric cooler coupled with a ThorLabs TED 200 temperature controller. A thermoelectric cooler (TEC) is a device that can pump heat from one side of the device to the other depending on the direction of the current.[15] The TEC uses a structure of p and n- type materials as seen in Fig. 27.

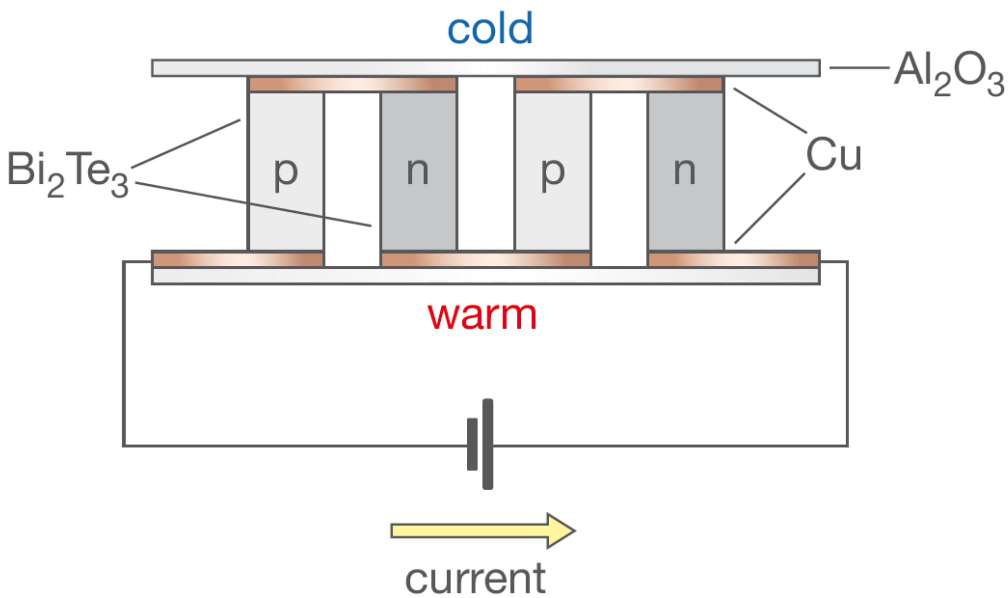

FIG. 27. Schematic of a TEC when a current is applied in one direction, the exchange of heat will flow towards the bottom of the device. If the current is reversed then the flow of heat will also be reversed.

The TEC requires the use of a heat sink to help establish a thermal difference between the two surfaces. Without a proper heat sink, the heat will have no place to go and a temperature difference cannot be established. This is accomplished by attaching the TEC to a large block of iron to act as a heat reservoir. This is sufficient because the capacity of the block of iron is large enough to be considered as a thermal reservoir. To ensure efficient heat transfer, a thermal compound is applied to fill in any possible gaps between the surfaces. The temperature is monitored using a thermistor that changes its resistance depending on the temperature. The temperature controller uses the resistance of the thermistor to determine the temperature of the diode. It has been noticed that as the resistance is increased, the temperature decreases, suggesting a negative temperature coefficient. The temperature controller uses proportional-integral-derivative (PID) control to maximize the controller's ability to maintain a steady temperature, as well as minimize the time required to reach a chosen temperature. It has been observed that the PID control provides a very stable temperature once it reaches the set value. However, once the value is changed, a considerable amount of time is required for the system to reach equilibrium. It is important to note that as the temperature rises, the wavelength will increase. For this particular system raising the temperature raises the wavelength only by about 0.1 nm. However, raising the temperature makes it easier to adjust the grating to reach 670.8 nm.

R. **Wavelength detection**

For this experiment it is essential to determine the wavelength at which our laser operates and to do this I will use a Burleigh WA-2500 wavemeter. All that is needed to determine the wavelength is to properly align a fiber-optic cable that is fed into the back of the wavemeter. The wavelength of the laser light is determined by a scanning Michelson interferometer, photodiode, and a microprocessor[16]. The incoming laser light is split into two beams via a beamsplitter with one beam going into the scan mechanism and the other goes to two mirrors used for calibrating the instrument. Both of the beams are then reflected back to the beamsplitter and then to a photodiode detector while maintaining collinear alignment so that the beams will overlap one another. The beam incident on the scan mechanism will experience a different path length determined by the displacement of the mechanism. When the two beams are recombined, interference fringes are present as a result of constructive and destructive interference. The photodiode is used to detect these interference patterns and the information is sent to a processor. To calculate the wavelength the displacement of the scan mechanism must be precisely determined. The scan mechanism displacement is then sent to the processor for interpretation of the two inputs. The wavelength can then be determined by

$$\lambda = \frac{2\Delta d}{\Delta m}. \tag{32}$$

Here, Δd is how far the scan mechanism is translated and Δm represents how many fringes pass over the photodiode.

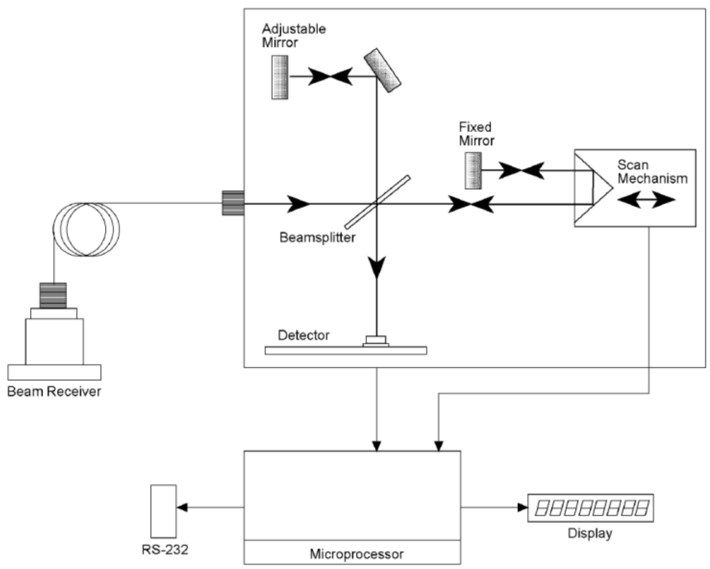

FIG. 28. Internal layout of the WA-2500 adapted from operating manual.

The WA-2500 significantly reduces the complication of determining the wavelength and provides fairly accurate results.

S. **Spectrum analyzer**

The Spectrum analyzer used in this experiment is made by Coherent Components Group and is designed to operate in a wavelength range of 650-750 nm. The spectrum analyzer uses two mirrors oriented as a Fabry-Perot interferometer with one mirror attached to a piezo-electric drive to allow the mirror to move, thus changing the length of the cavity. The cavity is created from two confocal, partially transparent mirrors to allow some of the light to be transmitted to the photodiode at the end of the spectrum analyzer (Fig. 29).

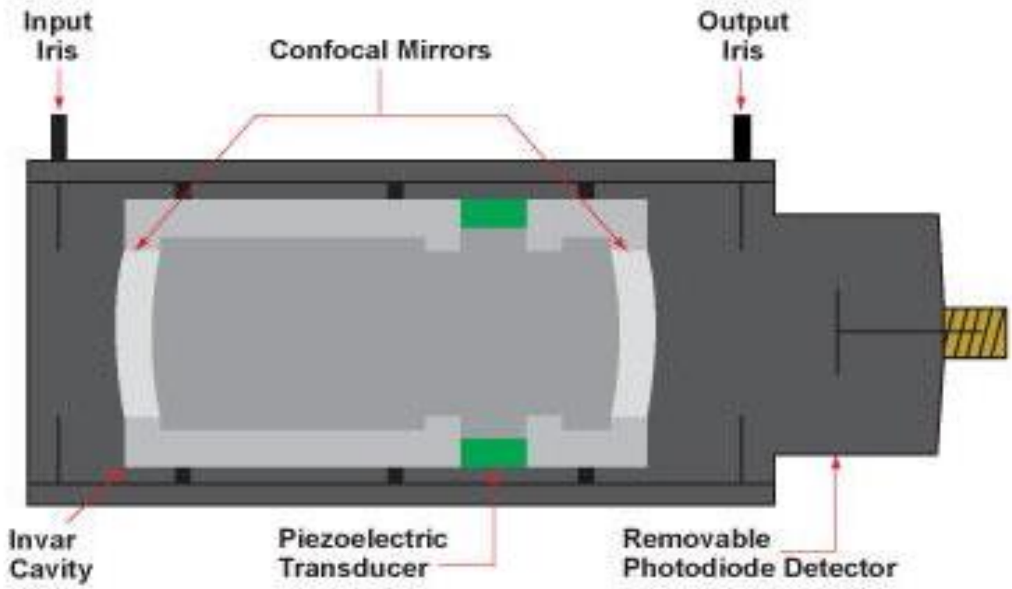

FIG. 29. A diagram of a scanning Fabry-Perot interferometer using two confocal mirrors as well as a photodiode detector located at the output. A voltage may be applied to the piezoelectric transducer to extend the length of the cavity. Adapted from ThorLabs[17]

It is important to note that a maximum of 40 volts can be applied to the piezo-electric element to adjust the length of the cavity or damage may occur. Only light with a wavelength that fits inside the cavity will constructively interfere and build up to significant amplitude resulting in a peak observed by the photodiode. Wavelengths that do not fit inside the cavity will destructively interfere and the output will be a minimum.

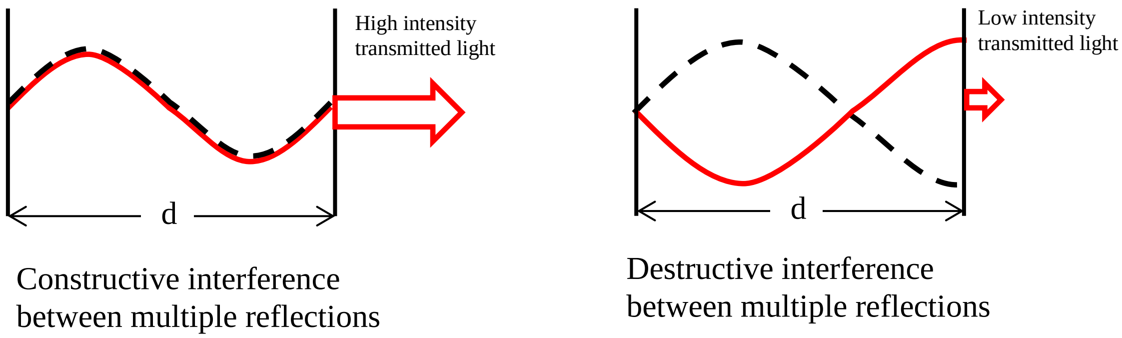

FIG. 30. Diagram of a Fabry-Perot cavity and the effects of constructive and destructive interference.

Our spectrum analyzer uses a confocal cavity, with a curved mirror set with a common focus. The resonance condition is that an integer number of wavelengths equals four times the mirror separation [18]

$$m\lambda = 4d \quad or \quad m\left(\frac{c}{f}\right) = 4d \tag{33}$$

Where *m* is an integer, c is the speed of light, *f* is the frequency, and d is the spacing between mirrors. The bandwidth of frequencies that can be measured without repeating the same transmission pattern called the free spectral range, and is given by:

$$FSR = \frac{c}{4d} \tag{34}$$

This particular spectrum analyzer has a free spectral range of 1.5 GHz. While tuning the ECDL with the control box, it is important to watch the output of the spectrum analyzer for signs of any irregularities in the output.

T. **Optical isolator**

For the laser to operate properly, it is important to isolate the laser system from any back reflections caused by collinear alignment of the apparatus. The elements of the apparatus are aligned so that they are collinear with the laser light for maximum performance and intensity. An element called an *optical isolator* acts like an "optical diode" for light, allowing to propagate in only one direction. It was noticed that prior to the use of an optical isolator, the output from the spectrum analyzer was not very stable and the wavemeter would not display a consistent wavelength. A ThorLabs IO-5-670-HP adjustable narrow band optical isolator was chosen because of its high transmission of 89% and its wide tuning range. The optical isolator's operation uses the Faraday Effect, in which a transparent material is placed in a magnetic field and polarized light is passed through the material in the direction of the magnetic field. The resulting output light is still linearly polarized but the plane of polarization will be rotated by an angle, β, to the incident polarization.[19]The rotation angle β is proportional to the strength of the magnetic field and the thickness of the material in the field,

$$\beta = VBd \tag{35}$$

Where B is the magnetic field strength, d is the thickness of the material, and V is the Verdet constant of the material placed in the magnetic field. The interesting characteristic of the Faraday Effect is that the rotation of the plane of polarization is independent of the direction of light, which is to say that any input light polarization will be rotated by β and any light propagation back through the Faraday rotator will also be rotated by β resulting in a cumulative rotation of the polarization. The optical isolator in our experiment also contains two linear polarizers, one at the input and one at the output that can be adjusted to allow tuning of the isolator. The linear polarizer easily allows light with the electric field oscillating in the same direction as the materials transmission axis (TA) to propagate through the material (Fig. 31).

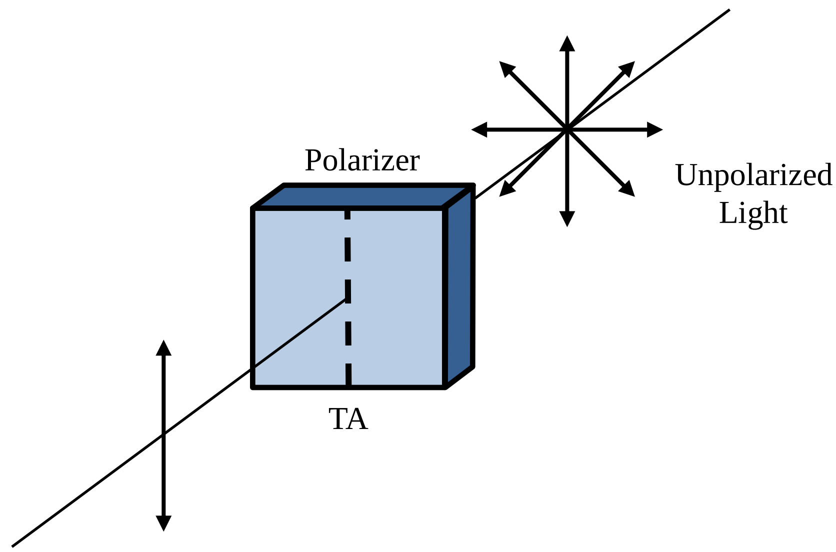

FIG. 31. Diagram of a linear polarizer and its effect on unpolarized light.

The light then encounters the Faraday rotator and the polarization of the light is rotated by 45 degrees from the previous polarizer's transmission axis. The light is then emitted through the second linear polarizer with its transmission axis aligned with the polarization emitted from the faraday rotator. When the reflections from the apparatus enter through the output of the isolator, the Faraday rotator will continue to rotate the polarization by 45 degrees in the same direction as the input beam resulting in a net polarization rotation of 90 degrees. The new direction of polarization is now perpendicular to the transmission axis of the input polarizer so no light will pass. The effects of a Faraday rotator arranged between two linear polarizers can be seen in Fig. 32.

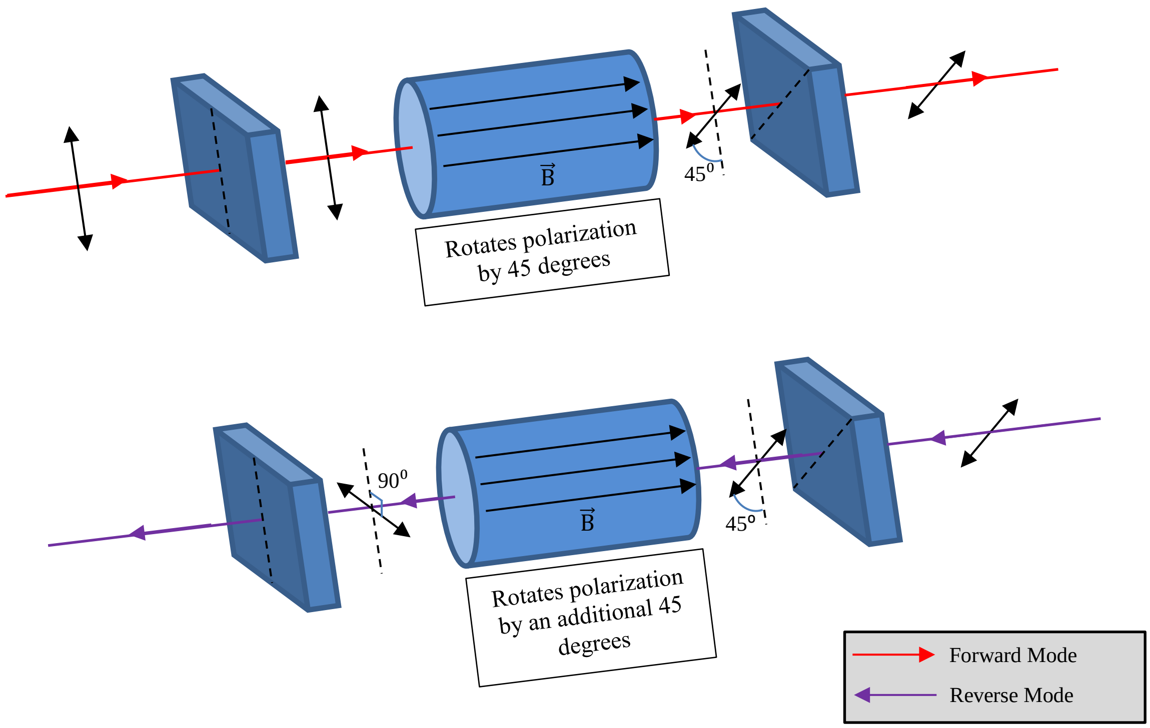

FIG. 32. A diagram illustrating the effects of a faraday rotator and two linear polarizers to reduce the light reflected by elements in the apparatus.

It is important to note that the light emitted from a laser diode should be polarized in one direction; however, the light from our diode does not appear to have one polarization but instead appears to be unpolarized, possibly indicating a problem in the laser diode operation. The extra polarization is "thrown away" and a beam of reduced intensity emerges from the optical isolator.

U. **ECDL linewidth**

Once the ECDL was operating as a single mode laser I found it useful to determine the line width of the output frequency. Once the linewidth is determined, it can be compared to other ECDL's linewidths to ensure proper performance has been achieved. To determine the linewidth of the lasers output, the full width at half maximum

(FWHM) needs to be calculated. This requires an understanding of the relationship between frequency and the amount of data points so that the oscilloscope data can be calibrated. This was done by scanning the spectrum analyzer to ensure that two peaks appear on the oscilloscope within the same voltage ramp. The distance between these two peaks is equal to 1.5 GHz, the free spectral range of the spectrum analyzer. Figure 33 is a plot of the data acquired from the oscilloscope,

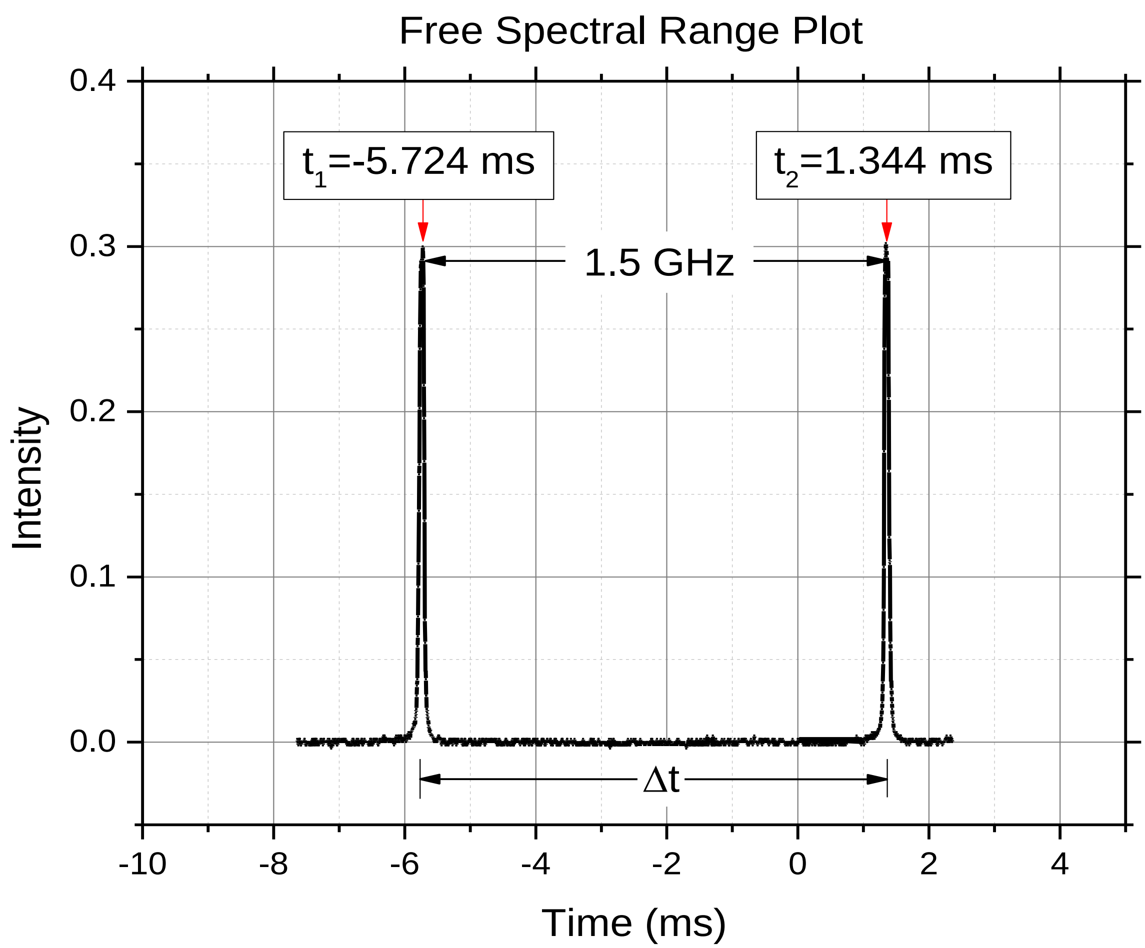

FIG. 33. Plot of the output from the spectrum analyzer. The distance between the two spikes is equivalent to the free spectral range of the spectrum analyzer.

Looking at the plot we can determine the ratio to be

$$\left|\frac{\text{FSR}}{\Delta\text{t}}\right| = 2.122 \text{ x } 10^{11} \ \frac{\text{Hz}}{\text{s}}.$$

We can now use this ratio to determine the linewidth of our peak at FWHM by calculating Δt.

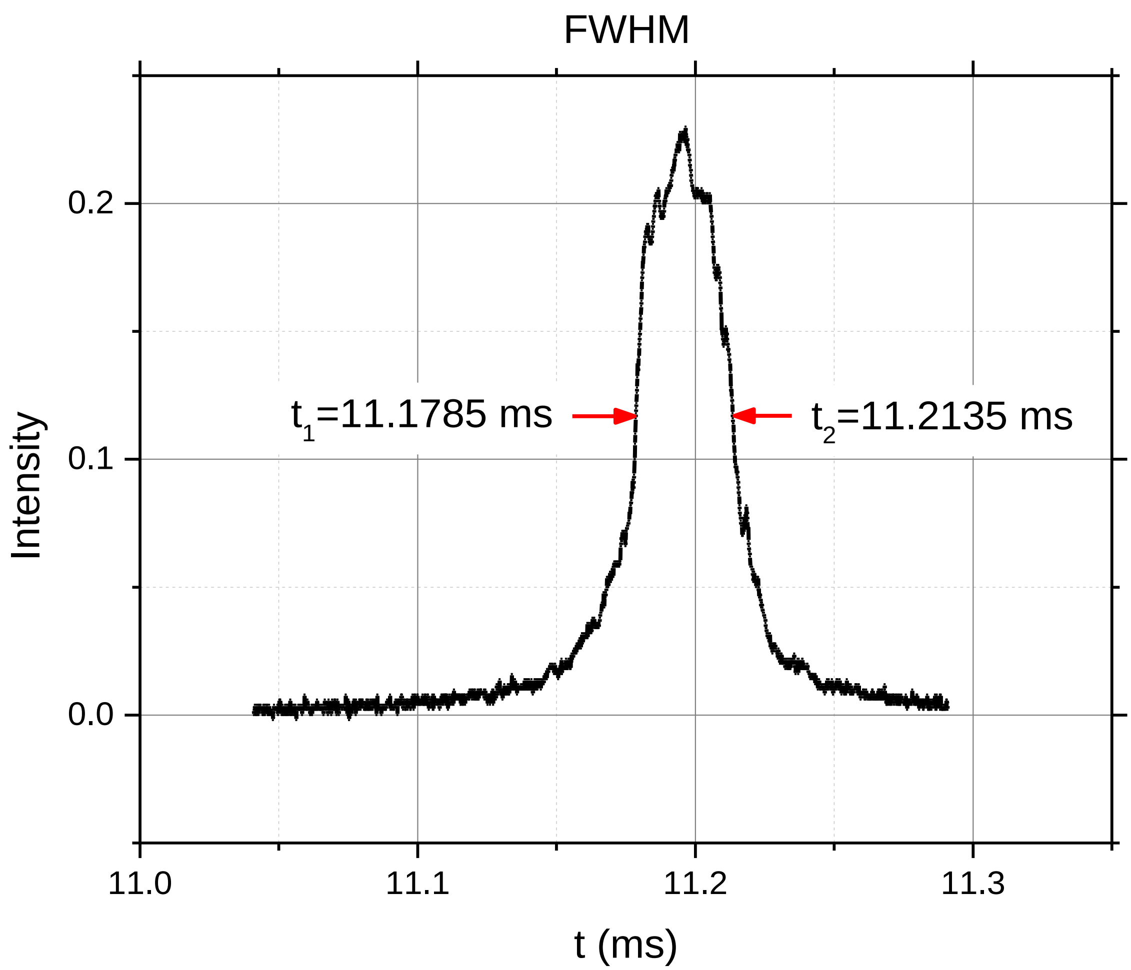

FIG. 34. Detailed plot of a single peak at a given instance in time.

As seen in Fig. 34, $\Delta t = 0.350$ μs. Now we can apply our ratio to find that the linewidth of our peak is equal to 7.43 MHz. The lineshapes involved are approximately Lorentzian, and the total linewidth is the sum of the linewidth of the laser and the linewidth of the spectrum analyzer. The data sheet for the spectrum analyzer states that its finesse is 275 at 676.4 nm. If we compensate for our operating wavelength, we can assume a finesse of 250. The linewidth of the spectrum analyzer is approximately 6.00 MHz. Therefore the actual linewidth of the laser is found to be 1.43 MHz. For a typical ECDL system we can expect a linewidth on the order of 1 MHz, corresponding nicely with our result.

VI. CONCLUSION

I have constructed an ECDL in the Littrow configuration for use in future experiments involving lithium. I have determined the tuning characteristics of the system as well as the linewidth. Further advancement of this project may require the implementation of a new laser diode, which has already been purchased. The ultimate goal for this ECDL is to us it to excite lithium atoms in an atomic beam. The atomic beam is of particular interest in the study of electromagnetically induced transparency, because the atoms in a beam will have fewer collisions and less Doppler effect than atoms in a cell, where such experiments are usually performed.

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